AN EFFECTIVE, LOW-DISTORTION LIMITING AMPLIFIER

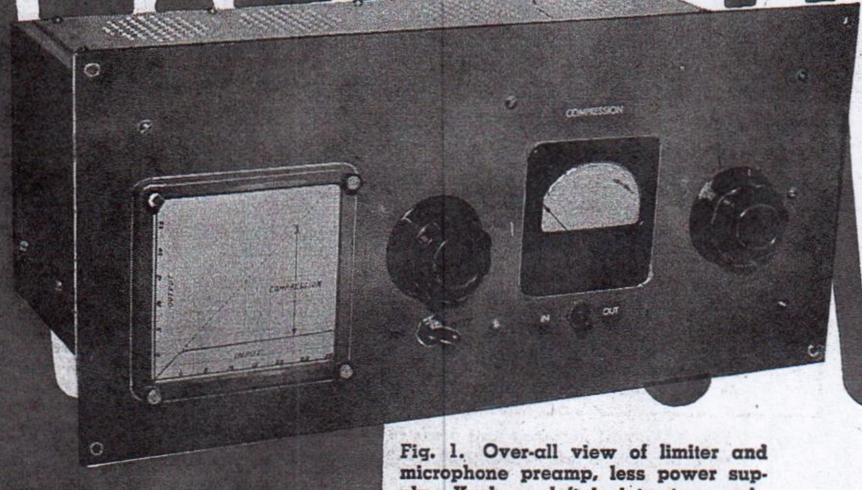

Fig. 1. Over-all view of limiter and microphone preamp, less power supply. Knob on left is interstage gain control in the preamp which adjusts the amount of limiting. The switches are to cut in high- or low-frequency compensation to emphasize speech frequencies, if desired. The chart is used to record the optimum settings.

By

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Construction details on a unit which offers negligible distortion and has a high degree of control leverage.

IT IS well recognized that an effective phone signal is one that is maintained at a high degree of modulation at all times. A completely modulated 250-watt signal is approximately as effective as a kilowatt signal that is only 50% modulated, and considering that a.v.c. action of the receiver adjusts the receiver volume in proportion to *received carrier,* the 250-watt signal would actually put out *more* volume from the speaker than would the kilowatt station.

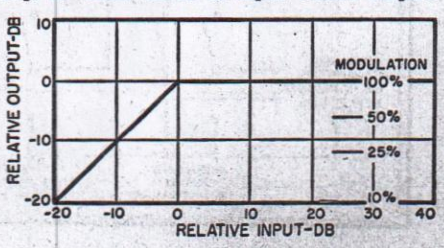
It is the desire of every station operator to find an effective means of keeping the modulation level as high as possible, but at the same time preventing it from exceeding the legal maximum. Many schemes have been advanced, such as clipping-filtering combinations and various types of limiting or compression amplifiers.

It is the intent of this article to describe one such device that has proven to be very effective, yet includes few of the usual disadvantages. The limiter to be described is the outcome of several years' experimentation and closely parallels several of the commercially built units designed for broadcast work.

It might be well to begin by reviewing the requirements to be met by the limiting amplifier. (1) The amplifier must be capable of large amounts of compression with negligible distortion in the important speech frequency ranges. (2) It must have a high degree of control leverage, *i.e.,* above the threshold point, the gain should virtually cease to increase for any further increase of input signal. The ideal curve of input plotted against output would be one that suddenly flattened out to a perfectly straight line having no slope. See Fig. 2. (3) The limiter must have a fast attack time. Irrespective of amplitude, the limiter must catch the first impulse and prevent it from exceeding the pre-determined maximum. (4) It should also have a reasonable recovery time; fast enough to allow the gain to rise between syllables to keep every word at maximum modulation, yet slow enough so that clipping of individual cycles does not take place in the important speech range of frequencies. (5) There must be no type of instability nor should any control surges get through to cause popping or thumping in the output of the device. The unit to be described qualifies on all these points and its effectiveness is acknowledged by those who have heard it operate.

It may be of interest to the reader to know why the author felt that clipping-filtering does not meet the requirements. A detailed discussion about transient response of filters, networks, and waveform distortion would be necessary to explain the deficiencies of the system. In a nutshell, the author believes it is much better to use a system that does not severely distort the waveform. Even after filtering, the clipper type of system exhibits an amazing amount of intermodulation products that cannot be eliminated, all of which seem to mask the intelligence of the signal and otherwise offset much of the increase in loudness. Also, due to the overshoot of a sharp cut-off type of filter when subjected to a square-wave type of impulse, an average loss of approximately 30% of possible modulation level must be maintained to prevent overmodulation. These factors made it desirable, in this instance, to concentrate on a compression type of circuit.

Fig. 2. Ideal curve of input versus output.



A compression, or limiting amplifier does not change the character of the waveform, unlike a clipper, but merely reduces the total size of the waveform to conform with certain pre-determined peak amplitudes. It does this instantaneously without detracting from the intelligence or articulation of the speech being transmitted. The manner in which this is accomplished can be seen from Fig. 3. If curve A of Fig. 3A is designated as the characteristic plate curve of tube V_1 (or V_2), Fig. 4, with no reduction in gain, an input voltage *E* impressed on the tube will result in a given output voltage *E'*. If a control circuit is arranged to change the gain of V_1 by shifting the operating characteristics and hence the *slope* of the plate curve in such a way that when the impressed input voltage is raised, the slope will change in the same proportion, then the output waveform will remain substantially the same size, irrespective of the amount of input voltage, as in Figs. 3B or 3C. In other words, it is the slope of the curve that is changed, and not the shape of the waveform, which remains a perfect replica of the input waveform, except for size. The dynamic curve of the gain reduction amplifier stage is essentially a straight line under all degrees of compression. This, then, is the key to the operation of the limiter. It is a dynamic device that provides a set of operating conditions suited to each part of the signal it encounters in order to maintain a certain maximum peak level at all times.

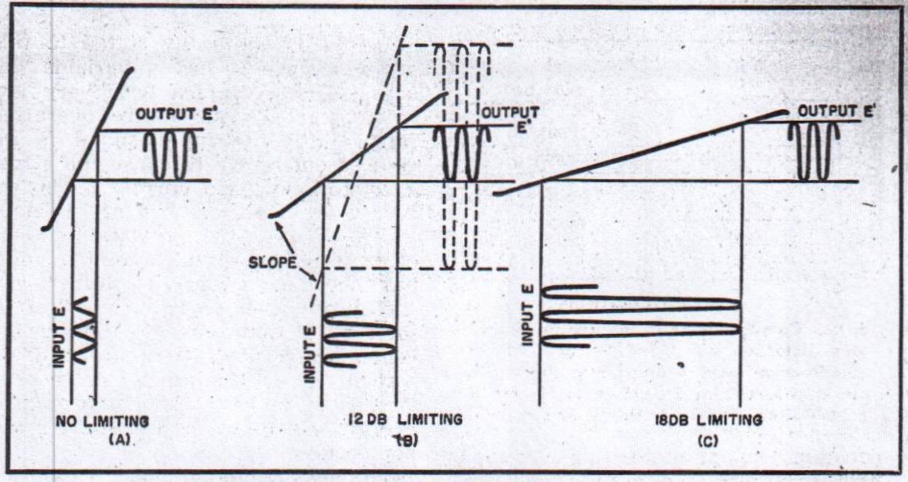
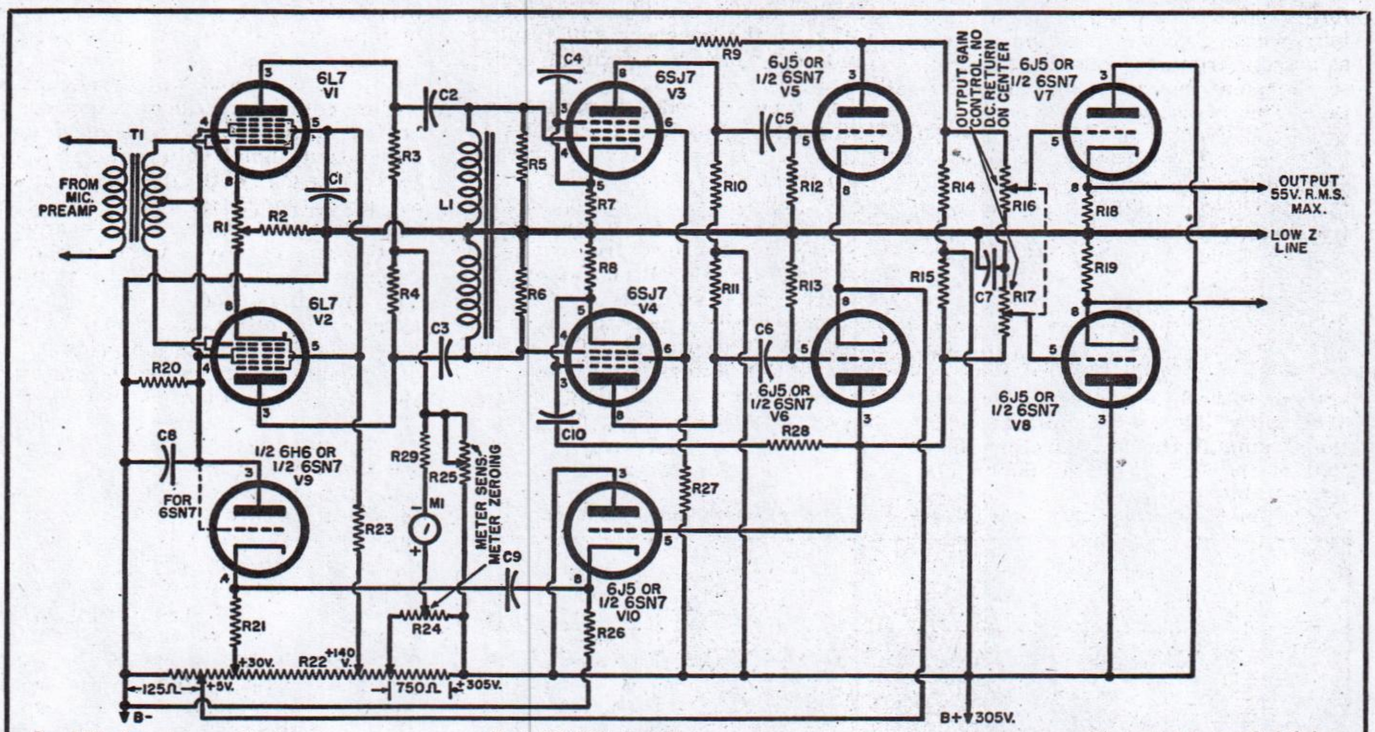


Fig. 3. Idealized characteristic curves of V_1 and V_2, Fig. 4. See text.

The complete diagram of the W6UAF limiter is shown in Fig. 4. To make the device most effective for amateur work, several measures have been incorporated that would not prove desirable in broadcast work. A higher degree of control ratio has been achieved, at the expense of distortion at extremely low frequencies. We are not concerned with small amounts of distortion at frequencies below 100 cycles, whereas such a compromise cannot be made in broadcast work. The recovery time of the control circuit has been made very short so it will effect its recovery between syllables instead of after several words have been spoken. This keeps the modulation high for each word or syllable, even when speaking at a rapid rate. This has also been done at the expense of low frequency distortion. Extremely fast attack time has been achieved through the use of a low impedance cathode follower circuit that will charge the time

Fig. 4. Complete schematic diagram of limiting amplifier. For an auxiliary power supply to be used with this unit, see Fig. 6.



R_1—100 ohm wirewound pot
R_2—250 ohm, 1 w. res.
R_3, R_4—25,000 ohm, 1 w. res. (matched ± 1%)
R_5, R_6—500,000 ohm, ½ w. res.
R_7, R_8—1500 ohm, 1 w. res. (matched ± 1%)
R_9, R_{28}—30,000 ohm, ½ w. res. (matched ± 1%)
R_{10}, R_{11}—250,000 ohm, ½ w. res. (matched ± 1%)
R_{12}, R_{13}—500,000 ohm, ½ w. res. (matched ± 1%)
R_{14}, R_{15}—75,000 ohm, 1 w. res. (matched ± 1%)
R_{16}, R_{17}—500,000 ohm dual audio taper pot
R_{18}, R_{19}—25,000 ohm, 10 w. wirewound res.
R_{20}—15 megohm, ½ w. res. (Measure after soldering in place to insure value hasn't dropped after heating)
R_{21}—100,000 ohm, ½ w. res.
R_{22}—10,000 ohm, 50 w. bleeder res. (with 4 adj. taps)
R_{23}—30,000 ohm, 1 w. res.
R_{24}, R_{25}—5000 ohm wirewound pot
R_{26}—20,000 ohm, 10 w. wirewound res.
R_{27}—500,000 ohm, 1 w. res.
R_{29}—10,000 ohm, ½ w. res.
C_1—.5 µfd., 600 v. capacitor
C_2, C_3, C_5, C_6, C_7—.1 µfd., 600 v. capacitor
C_4, C_{10}—1 µfd., 600 v. bathtub capacitor
C_8—.01 µfd., 400 v. capacitor
C_9—1 µfd., 400 v. bathtub capacitor
L_1—Sec. winding UTC Type 0-6 "Ouncer" trans. Pri. left open and unused (Do not substitute)
M_1—0-1 ma. d.c. milliammeter
T_1—Interstage trans. (Any high quality unit having sec. with accurately matched halves, such as UTC LS series or Stancor WF series, can be used. Sec. grid winding imped., nominal 50,000 ohms)
V_1, V_2—6L7 tube V_3, V_4—6SJ7 tube
V_5, V_6—Single 6SN7 tube or two 6J5 tubes
V_7, V_8—Single 6SN7 tube or two 6J5 tubes
V_9—6H6 tube or ½ diode-connected 6SN7 if other half is used for V_{10}
V_{10}—6J5 or ½ 6SN7 tube

Note: Except in the case of R_7, R_8, R_9, R_{28}, the nearest available RETMA standard value resistor may be substituted should the values specified be unobtainable, however each resistor must be matched in value with its corresponding mate on the opposite half of the push-pull circuits.

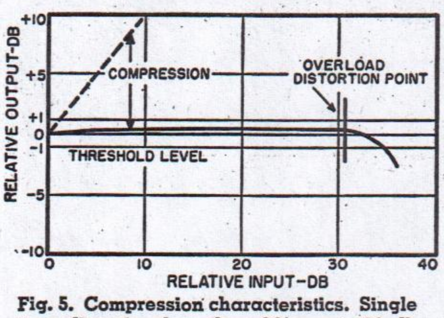


Fig. 5. Compression characteristics. Single tone distortion less than 2% up to 30 db compression for any frequency above 100 cps and less than 5% down to 50 cps (a steady-state tone). See discussion in text.

constant capacitor at a very rapid rate. Push-pull circuits are used throughout to prevent undesirable thumps, and other phenomena attributable to control circuit surges, from appearing in the output of the speech system.

Upon examination of Fig. 4, it will be noticed that the control voltage is sampled off only one side of the waveform in a half-wave rectifier circuit. In broadcast work this would be undesirable since it would allow certain voices to sound much louder than other voices or music depending upon the polarity of the speech waveforms. This is no problem to the amateur, whose object is to sound as loud as possible from only one sound source, so the point can be taken to advantage. This is discussed later on in this article.

The circuit consists of three principal parts: the gain reduction stage, the stabilized amplifier, and the control circuit. Also included as a somewhat optional feature is the output coupling stage.

The variable gain stage consists of a pair of 6L7 tubes operated in push-pull, with the signal applied to one set of control grids and the control voltage to both sets of control grids. This gives the control voltage additional amplification or leverage over that of the signal voltage alone. The 6L7 tube is admirably suited to this purpose since it has a variable mu characteristic coupled with very low distortion over the entire operating range until the input signal is increased suffiсently to cause the signal grids to draw grid current. This latter factor becomes evident at input levels in excess of approximately 31 db of compression at which point the output becomes severely distorted and the output level drops abruptly. It is interesting that once the limiter becomes overloaded, the output *drops* instead of continuing to increase so that even under these circumstances overmodulation of the transmitter will not occur.

The gain reduction stage is followed by a two stage amplifier having certain critical requirements. The gain-frequency characteristics have been carefully selected to make the amplifier stable under all conditions of compression. Stability has been made high by means of inverse feedback and other features make it relatively insensitive to control thumps. The design of this portion of the limiter is extremely important, since it is essentially a part of a very high gain feedback loop. The mechanical analogy is the governor-controlled engine. Any mechanical instability causing erratic or sluggish operation of the governor will result in "hunting," which is a form of oscillation.

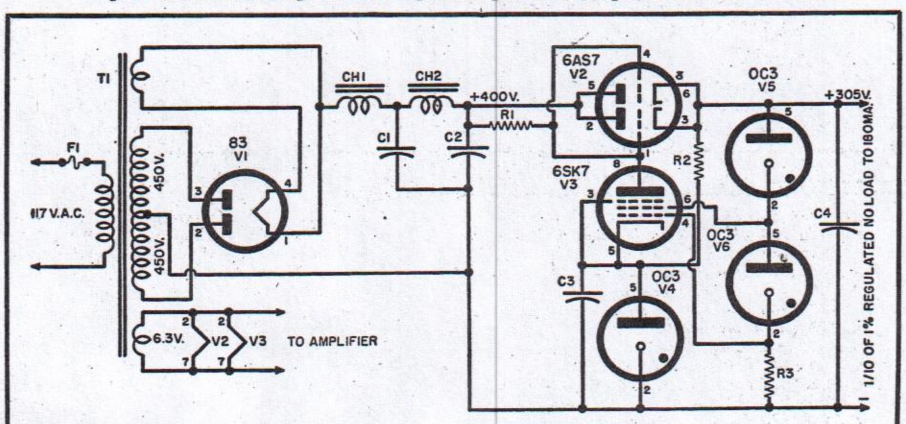
Any type of feedback path formed by a control circuit that samples the output of the device being controlled is capable of oscillation unless the frequency response of the loop is carefully controlled over many octaves, especially when the control leverage is very high (large feedback factor). The low frequency design is of great importance because perhaps it is the most difficult to control. It is in order to meet this design requirement that the inductance, L_1, is used between the gain reduction stage and the remainder of the amplifier. Because of its effect on the control circuit loop, the requirements for the secondary ratings of the interstage transformer from the preceding microphone stages are quite critical. This transformer must have a well balanced secondary winding with low residual parameters.

Another similar oscillation is possible in the limiting amplifier if any control surge gets through the signal portion, becomes amplified, and is again sampled by the control rectifier. The frequency of oscillation is determined by the discharge time of the time constant circuit, C_8 and R_{20}, the circuit that normally determines the recovery rate of gain limiting. This oscillation is not likely to take place with matched tubes and components in a push-pull type of circuit. Means for balancing the circuit for dynamic operating conditions are provided by adjustment of R_1.

The high frequency response of the control loop determines the behavior to impulses or transients. This defines how quickly gain stability is obtained after a sudden increase in gain has taken place. Poor high frequency response of the loop will cause the control to overshoot. The output will then decrease below that desired, then above, etc., in a damped type of oscillation before equilibrium is established for the new steady-state value of input signal. Careful design of the response and amount of damping insure that overshoot will be negligible.

The control rectifier is biased so that limiting action is delayed until the output signal voltage exceeds the bias voltage. With the bias voltage set at 30 volts, the output signal on the side of the circuit that is sampled by the control circuit cathode follower cannot greatly exceed 30 volts since the amount beyond which it actually exceeds 30 volts is impressed directly as a negative bias on the grids of the 6L7 tubes. There is no such limitation to the level encountered on the opposite side of the push-pull amplifier. This means that if the side of the signal appearing in the controlled side of the amplifier is chosen to modulate in the *downward* direction, the absolute limit of modulation will be the desired amount on *negative* peaks, but any unsymmetrical speech wave having high peaks in the upward direction is not limited, except in its normal proportion to the height of the negative peak. Thus if the transmitter is capable of a very high degree of modulation in the positive direction, compared to the negative direction (as most transmitters are that are not skimpy on design) advantage can be made of it. This will amount to some 6 db or better. There will be no difference in the height of the positive and negative peaks on sine-wave tone. Unfortunately speech does not consist of pure sine-wave tone and the energy content is much lower for the same peak amplitude, however the most can be made of the normal asymmetry existing in male speech by allowing the highest peaks to go only in the direction that can most easily be accom-

Fig. 6. Schematic diagram of a regulated power supply for limiter amplifier.



R_1—470,000 ohm, 1 w. res.
R_2—20,000 ohm, 10 w. wirewound res.
R_3—5000 ohm, 10 w. wirewound res.
C_1-C_2—10/10 μfd., 500 v. elec. capacitor
C_3—.1 μfd., 600 v. capacitor
C_4—10 μfd., 450 v. elec. capacitor
CH_1, CH_2—10 hy., 200 ma. filter choke
F_1—3 amp. fuse
T_1—Power trans. 450-0-450 @ 200 ma.; 5 v. @ 3 amps.; 6.3 v. @ 5.8 amps.
V_1—83 tube
V_2—6AS7 tube
V_3—6SK7GT or GT tube
V_4, V_5, V_6—0C3/VR-105 tube

modated without distortion. Failure to regard the importance of this factor will result in seemingly weak modulation should the wrong speech wave polarity be observed, even though the scope shows consistent 100% modulation is being achieved on negative peaks.

The particular values chosen for the recovery-time-constant circuit were selected to allow the fastest possible attack time. The recovery rate is determined by the speed with which C_8 discharges through R_{20}, according to the formula $T = CR$. T is the time measured in seconds, C is in microfarads and R is in megohms. This formula gives the time required for the voltage to decay to 63% of its steady-state value after the applied control voltage has been removed. The value of 15 megohms and 0.01 μfd. gives a recovery rate of .15 second. The actual value is probably closer to .2 second if the stray capacity of the transformer winding of T_1 is included as part of C_8.

The attack time is determined by the series impedance of the source used to charge C_8. The resistance of the diode is probably in the vicinity of 300 ohms and the source impedance of the cathode follower is approximately $1/G_m$. Using published values of operating characteristics that most nearly match the actual operating conditions of the cathode follower, we obtain a source impedance of 385 ohms. This, added in series with the 300 ohm diode resistance gives a total charging resistance of 685 ohms. The charging time would be (neglecting the 15 megohms across the capacitor) .01 x .000685 second. If we round off the .000685 to .0007 and assume some stray capacity in the transformer, we arrive at a time of approximately 7 microseconds. This is fast enough so that for all practical purposes the attack time can be assumed to be infinite for any impulse we propose to transmit having a frequency limitation of from 3000 to perhaps 10,000 cycles. It can be shown that if any appreciable overshoot does exist on the modulated carrier, it is probably due to poor transient response of the modulator rather than actual overshoot of the compression amplifier.

Thus, in order to utilize the full effectiveness of the limiter, the audio stages following the unit should be very carefully designed for minimum phase shift and flat response. A poor response curve following the stages of compression will result in persistent overmodulation at certain frequencies, or if this is corrected by lowering the gain, will necessitate the reduction of the average level of modulation. Restricted frequency range of the modulator will result in poor transient response and will cause hangover on steep wavefronts and result in shot type overmodulation. Phase shift of the relative frequency components will cause severe shifting of energy content-*vs*-peak power of the wave after the initial complex wave has already been limited by compression. This will cause wide variation in gain after it has supposedly been set to a definite maximum in the compressor. This would limit the effectiveness of the gain limiter as a device to prevent overmodulation.

Design the remainder of the modulator for the best frequency response possible even if the desired range is only that of the speech frequencies. Any frequency shaping or limitation *must* take place somewhere in the microphone preamplifier stages *preceding* the limiter.

The output circuit consists of a direct coupled, cathode follower circuit. This is an optional feature that performs the impedance transformation without the use of a costly transformer and allows the use of a simple dual volume control for the output gain control of the amplifier. It is to be noticed that d.c. appears on these leads and should be isolated with capacitors at the far end of the output leads before entering the input of a modulator, or if fed into a line-to-grid transformer means must be taken to keep the primary winding at d.c. potential above ground and to provide a large (25 μfd.) capacitor from the center of the winding to ground as a bypass.

There is a certain maximum output voltage which can be obtained directly from the limiter. This limit is approximately 55 volts r.m.s. which allows considerable margin for speech waves having low energy content. The limitation is caused by certain requirements of the feedback loop in the two stage amplifier. This feedback is always

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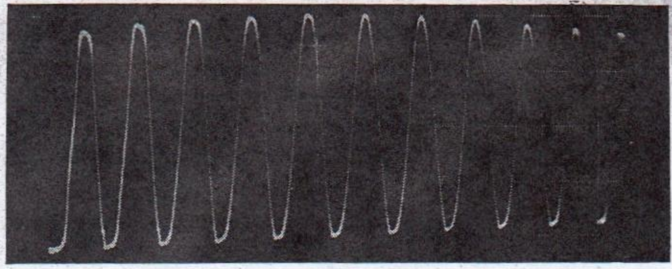

Fig. 7. Actual photo of output waveform when a 1000 cycle note is keyed. Triggered scope sweep started just as signal was keyed on. The oscillogram shows the first ten cycles after a signal was applied. This, and the other scope patterns, were taken with a Speed Graphic from the face of a Tektronix Model 514-D scope. The control rectifier sampled the side of the waveform that appears on the bottom of the pattern shown.

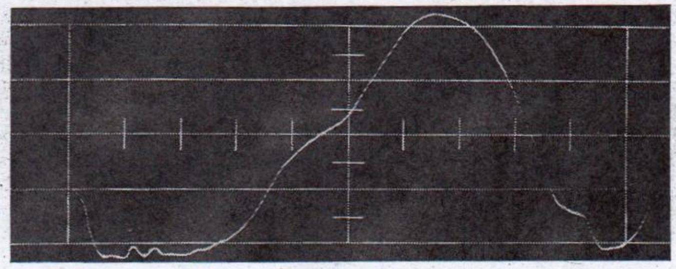

Fig. 8. Photo of first cycle undergoing compression in a wavetrain at 1000 cycles as in Fig. 7. Note the control circuit acts to make the first wave square-topped since the control cannot act until the actual signal exceeds the control bias voltage. The slight irregularities are due to the constants of the various feedback loops, as discussed in text. Circuit components were chosen to minimize these irregularities. Note that size of wave would be ten times as large had compression not taken place, barring overload of tube characteristics.

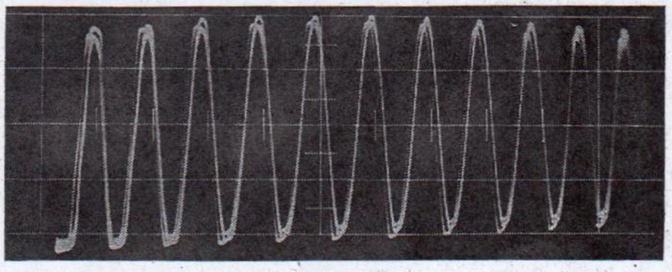

Fig. 9. Camera left open to record three separate, successive keyed 1000 cycle wavetrains at 20 db of compression. They do not precisely overlap because triggered sweep is more accurately activated with a pulse-type waveform than with sine wave.

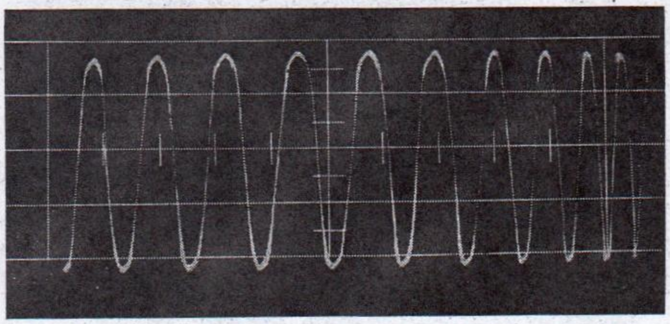

Fig. 10. Photo of first ten cycles of keyed 20 kc. note. This high frequency was immediately arrested on the first cycle, showing the effectiveness of the fast attack time. Waveform clipping exhibited in this and in all the preceding waveforms is more severe than would normally be encountered in speech material because the unit was keyed into very deep compression from a "no-limiting" condition. Unlike the keyed signal, the human voice usually requires several cycles to build up to maximum value, and the limiter has an opportunity to operate on a number of cycles of the wavetrain before the highest maximum occurs. The keyed tone is an especially severe test. Very little waveform clipping, except on the first cycle, will occur on normal speech wave under standard operating practice.

signed to work into low impedance loads, a step-up transformer between transmitter and antenna will effectively prevent loading.

In cases where difficulty is experienced, the length of the coax should be checked. A quarter wavelength of coax line can be found from the formula:

Line length (*in inches*) $= 1948/f$ (*in mc.*) A coax line which figures within a foot or so of any odd multiple of this value, on any band which you intend to work, should be carefully avoided. —30—

Limiting Amplifier

(*Continued from page* 63)

a certain fraction of the output voltage and is re-inserted in the cathode circuit of the first stage. The actual fraction is determined by the proportions of the resistor making up the voltage divider consisting of the series 30,000 ohm resistor and the 1500 ohm cathode resistor. Roughly 5% of the output voltage to ground appears at this cathode. Since the feedback voltage must not exceed the cathode-to-ground voltage of the stage in which it is inserted, this fraction cannot exceed approximately 3 volts. Thus the source used to derive this fraction cannot then exceed approximately 60 volts. The output consists of the total of both halves, so there is then effectively a maximum of 120 volts peak-to-peak available. The gain of the following speech amplifier or modulator should be adjusted so that less than 55 volts r.m.s. sine wave is required to completely modulate the transmitter.

The meter circuit is similar to the usual bridge type, upward-reading "S" meters used on communications receivers. It is so connected that it will swing upward when the plate current on the 6L7 tubes decreases with limiting action. This indicator should be calibrated and adjusted so that with 10 db of measured compression, it will read half scale. Actual compression is the measured difference in change of level occurring in the output for a given change in input level. For instance, if the input level is raised 20 db and the output level increases only 15 db, the unit has gone into 5 db of compression. This meter sensitivity is adjustable by means of R_{24} and R_{25}. The two adjustments interlock, so that changing the sensitivity by adjustment of R_{25} necessitates a re-adjustment of R_{24} to set the electrical zero scale when the unit is not under compression. The resulting scale will be nearly logarithmic in nature.

The unit is housed in a small cabinet that can rest on the operating table next to the receiver. The power supply is mounted remotely along with other supplies in the transmitter so no trouble would be experienced with hum induction from the transformers and chokes.

Parts layout is not critical but should follow conventional wiring practice and placement of parts typical of audio amplifiers. It is advisable to keep lead lengths short.

All resistors in the push-pull stages should be accurately matched with an ohmmeter as closely as possible. Substitute values may be used for those shown if the exact resistor values are unobtainable except in the case of certain resistors so indicated in the parts list. In general, however, the values chosen should not depart more than 20% from the values given and in particular no substitutions should be attempted that will drastically affect the feedback loop. Deviations in this part of the circuit will create distortion characteristics that are unpredictable and will affect circuit stability. Operating voltages should be adhered to exactly. For slightly different supply voltage, adjust the operating circuit voltages to the same *percentage* of the total supply voltage available.

Tubes should be chosen, for exact match, with a transconductance tube checker. The 6L7 tubes in particular should be chosen for the same gain characteristics for each corresponding control grid.

A power supply of extremely low source impedance is required, preferably regulated. Common coupling from a supply of high source impedance will result in a low-frequency oscillation having a repetition rate of about 1 cps or longer. A suggested regulating arrangement is shown in Fig. 6.

For proper operation, the initial adjustment to be made after the circuit voltages have been proportioned to the values shown, is that of the proper adjustment of the balance control in the cathode circuit of the 6L7 tubes. This resistor, R_1, is to provide dynamic balance so that control surges will not appear as thumps in the output. At extreme settings or with poorly matched tubes it is possible that the amplifier will oscillate. Through a suitable voltage divider, arrange to sample about 1 volt cf 60-cycle a.c. from the 6.3 v. heater supply. With one side grounded, put this test voltage on the plate pin of V_9 or on the secondary center tap of T_1, whichever is more accessible. Simply adjust R_1 for minimum output of the limiting amplifier. After completing this adjustment, remove the test voltage. This adjustment may require touching up from time to time as the tubes age.

Finally, as discussed previously, the speech waveform polarity should be observed throughout the system so that (1) the peaked side of the wave goes through the limiter on the uncontrolled side of the amplifier, *i.e.*, the part of the wave having the shallow side most consistently should be the one that feeds through the half-wave control rectifier. This is done simply by selecting the correct choice of polarity of the microphone leads. (2) The peaked side of the wave after compression should be polarized so that it modulates the transmitter in the *upward* direction. This is done by reversing the connections to one winding of the modulation transformer, if necessary. These polarities can easily be seen in a scope presentation by observing the audio waveform while sounding a vowel such as "Oh" or "Ah," which are excellent test units for checking the limiting amplifier.

In use, the output gain control sets the absolute modulation percentage of the transmitter. An input volume control in the microphone preamplifier stages of the speech system will set the input level to the compressor and thus determine the amount of compression that takes place. If the microphone preamplifier is arranged to suppress the low frequencies and emphasize the speech frequencies, it will be possible to take advantage of as much as 20 db of indicated compression without any ill effects. With flat amplification it will be necessary, or at least advisable, to limit the indicated compression to only 10 db.

This circuit will compress up to better than 30 db without distortion and the output rise is less than 1 db at 30 db of compression, or a control ratio of better than 30 to 1 for any level above the threshold point.

EDITOR'S NOTE: *You will note that in the schematic diagram of the power supply, Fig. 6, the 6.3 volt winding is floating and is not tied to ground. In the author's model, he had one side of the filament winding grounded. This, of course, does not follow sound engineering practice because under this condition the potential between cathode and heater of V_2 would be 305 volts. The maximum rated potential is supposedly 300 volts. Again, the potential difference between the cathode and heater of V_3 is 150 volts while the maximum allowable rating in this case is approximately 90 volts. In both cases the author has not designed his unit within specified ratings. He has, however, operated his unit under the grounded condition for some 5 years and hasn't lost any tubes as yet. There is no reason to believe that anyone following his idea would run into any particular trouble.*

For good design practice, however, this should be corrected. There are several ways in which this condition can be overcome. One way would be to operate the heaters at a potential of 75 volts above ground. This would place all tubes within their ratings and would also have the added advantages of biasing the low-level heaters for hum reduction. The simplest way to achieve this condition is to return the heater winding center-tap to a point 75 or 80 volts above ground on the main bleeder. In doing this, connect a 100,000 ohm isolating resistor in series with the center-tap of the heater winding to the 75 or 80 volt point on the main bleeder.

If this suggestion is followed, it would make it necessary to obtain test a.c. voltage, mentioned under the adjustment procedure, from a separate source so that one side would be at ground potential. -30-