Impulse Noise in F-M Reception

An investigation into the nature of impulsive noise in frequency modulation receivers, making extensive use of oscillographic records. The relative effects of the plate-volt and grid bias types of limiter on impulsive noise are compared and recommendations made to insure maximum noise reduction

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IMPULSIVE noise in frequency-modulation receivers has already been studied and reported by M. G. Crosby[1] and others. The purpose of the present article is to carry out the study in more detail. Certain theoretical considerations are presented and oscillographic confirmation shown.

When a shock, such as a noise pulse, is applied to the input of a radio receiver, a wave train or pulsation passes through the amplifier. The output of the final stage of the amplifier is a wave train which is characteristic of that particular receiver. The frequency of the wave train is the frequency of the center of the pass band, and the time duration is $1/f_c$ where f_c is one-half of the bandwidth. Typical response waveforms are shown in Figs. 1A, 1B, and 1C. These oscillograms were taken on the 5 Mc intermediate frequency amplifier of a frequency modulation receiver having 200 kc bandwidth. In the cases illustrated the time duration is about $\frac{1}{100{,}000}$ or 10 microseconds. Thus, there are about 50 cycles present in the main portion of the wave train. The shape of the envelope of this wave train is a function of the shape of the selectivity curve. There is a tendency for the voltage envelope to rise to a peak, drop to zero, and then reappear in the form of a secondary lobe with the phase of the radio frequency wave reversed. The size of the secondary lobe is a function of the shape of the nose of the selectivity curve. A slightly double peaked selectivity curve results in a marked secondary lobe as shown in Fig. 1A. The phase of the r-f wave reverses at the valley between the lobes. A flat-topped selectivity curve gives a smaller lobe as shown at B. The lobe disappears as shown at C if the selectivity curve is round nosed. The valley between the main lobe and the secondary lobe goes to zero as in A if the selectivity curve is symmetrical. If one peak of the selectivity curve is higher than the other, the valley between the lobes does not go to zero as shown at D.

When a wave train such as that shown in Fig. 1A is fed to a discriminator of the type usually used in frequency-modulation receivers, the output has the form shown in Fig. 1G. If the circuit were perfectly balanced, the output would be zero for this condition. The residual wiggles are due to slight imperfections in the balance.

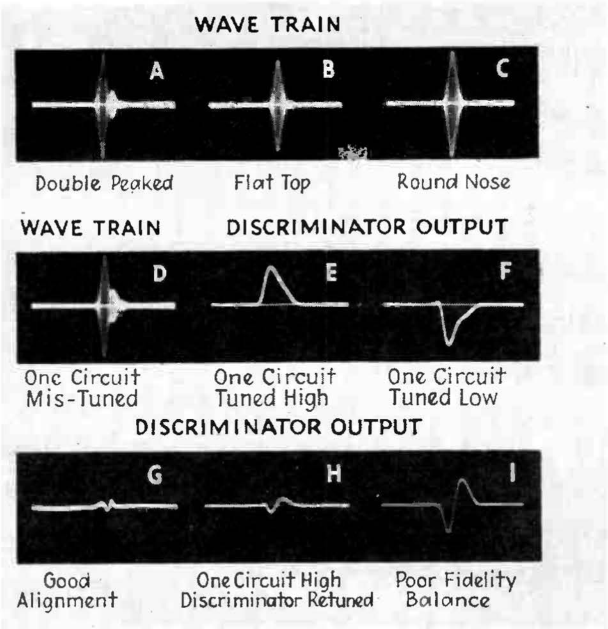
If one of the circuits of the receiver is detuned so as to give a selectivity curve with the low-frequency peak higher than the other, producing a wave train as in Fig. 1D, the discriminator output has the form shown at E. If the circuit is tuned to the other side making the high-frequency peak greater, the discriminator output changes to that shown at F.

Similar curves to E and F are obtained by mistuning the secondary of the discriminator one way or the other. Thus, it appears that the output of the discriminator goes plus or minus on the oscillogram according to whether the selectivity curve has more area above or below the frequency of resonance of the discriminator secondary. Oscillogram H of Fig. 1 shows the result of having the low-frequency peak exceed the high-frequency peak and of attempting to compensate by discriminator tuning. The indication is that the frequency of the pulse varies slightly with time for this condition.

The output network of the discriminator consists of two separate diode output circuits connected in series. The fidelity of these two circuits should be the same for a good balance, but this is not usually obtained. The output circuit is grounded on one side instead of in the center. This usually results in more capacitance across one side than across the other. This can be compensated for by adding capacitance to the other side. The effect of a capacitance unbalance of 10 micromicrofarads across 100,000 ohms is shown at I in Fig. 1.

Change of Tuning with Signal Strength

An unfortunate effect is the change in tuning with signal strength. This is illustrated in Fig. 2. The oscillograms of this figure were taken in the output circuit of a limiter. Limiter action was obtained because of grid current and because of the low plate voltage employed. At A the input level was too low for limiting to take place. The narrow neck between lobes indicates accurate alignment. The oscillograms at B and C were taken at progressively higher signal levels. The deep valley between lobes is missing indicating that certain circuits were detuned. The corresponding oscillograms of discriminator output are shown at D, E and F. The fact that E and F go negative shows that certain circuits are tuned to a lower frequency at the higher signal level. The circuit which is detuned most is the grid circuit of the limiter. This is proved by the next six oscillograms. These repeat the conditions of the preceding six except that the grid of the limiter is now fed by a tuned circuit having 600 micromicrofarads instead of 100 micromicrofarads for a tuning condenser. The detuning at high signal



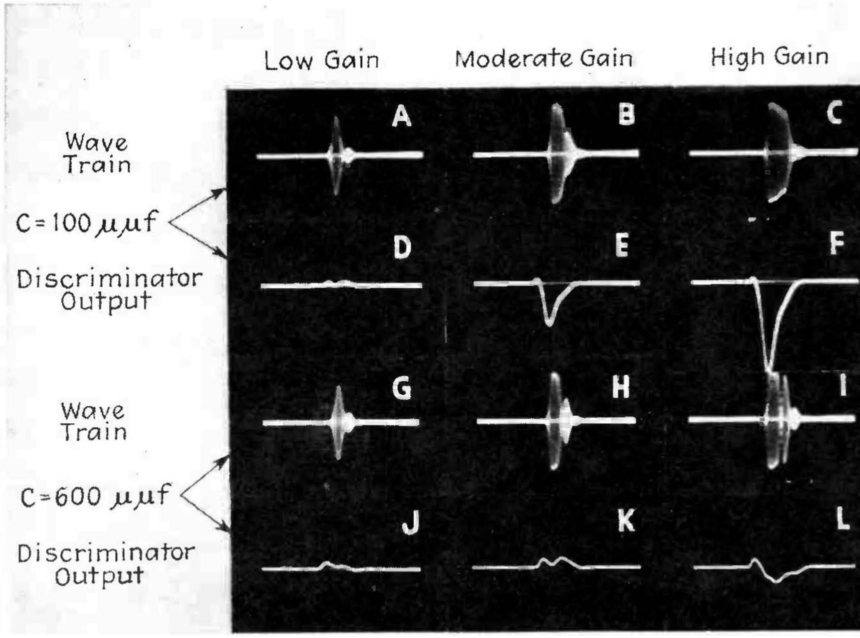


Fig. 1—Oscillograms of noise wave train and output of discriminator for various conditions of tuning

Fig. 2—Oscillograms of noise wave train and output of discriminator showing detuning due to grid current at higher amplitudes

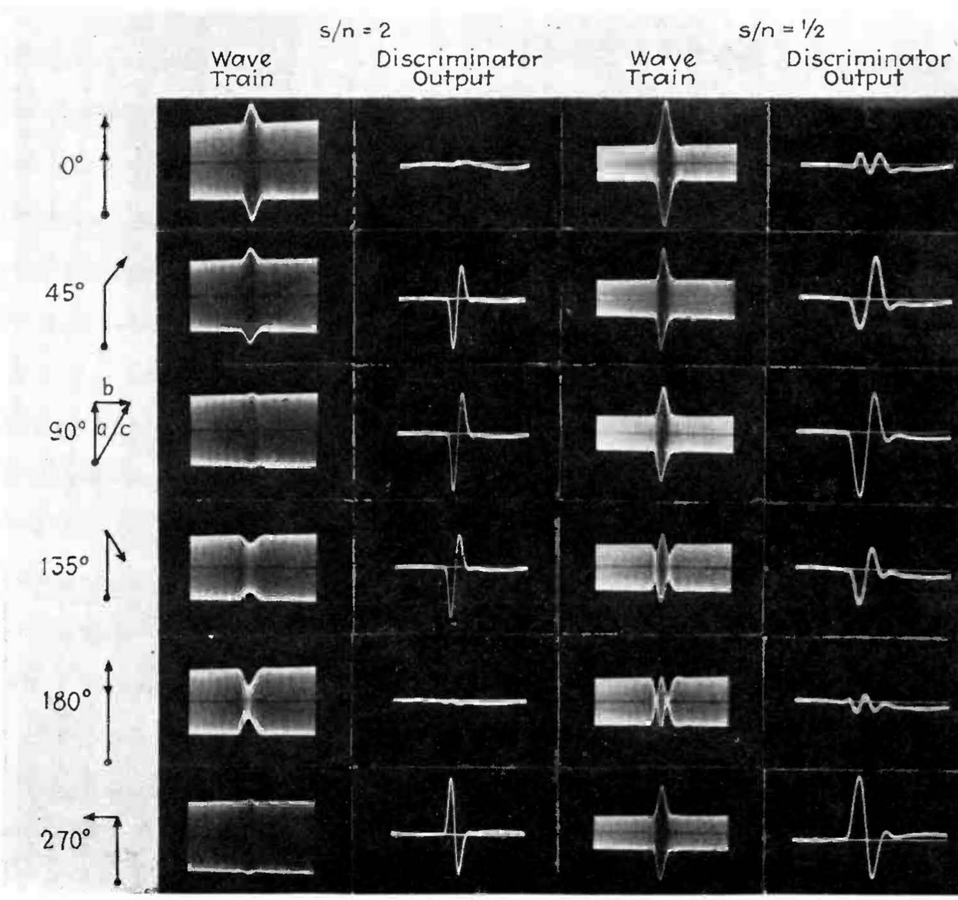


Fig. 3—Right, oscillograms of noise and discriminator output for various phase angles between the noise impulse and signal at two ratios of signal-to-noise with the carrier centered in the pass band

level is correspondingly less as illustrated by the deep valley between lobes at H and I and the smaller negative deflection at K and L.

The detuning caused by grid current can also be minimized by other methods. If the affected transformer is made broader than the preceding stages the detuning will not affect the overall performance. It also helps if the Q of the primary and the Q of the secondary are equal and if the coupling is less than critical in the affected transformer.

Noise and Signal Applied Together

When signals are being received, all the foregoing comments will apply only if the noise exceeds the carrier by about ten times or more. It is more usual for the noise to be less than the carrier or about equal to it. Under these conditions the noise output is a function of the reaction between the noise wave train and the carrier wave. The noise may come through purely as amplitude modulation, as frequency modulation, or as both, depending on the relative phase angle between the noise wave and the carrier wave.

To demonstrate these facts with an oscillograph it was necessary to build some special equipment. The difficulty with ordinary equipment is to synchronize the impulse generator with the signal generator so that the relative phase stays constant. Synchronization is obviously almost impossible with separate sources. To get around this difficulty the two waves were obtained from the same source. The source chosen was a 10,000 cps oscillator which was fed into two channels. In one channel the frequency was multiplied through a succession of stages up to the desired frequency of 5 megacycles. In the other channel the 10,000 cps wave was used to generate very narrow unidirectional pulses at the rate of 10,000 per second. The impulses and the 5-Mc signal were applied simultaneously to the input of a 5-Mc amplifier having a 200-kc bandwidth. Since the carrier wave and the impulses had a common source, the wave trains due to the impulses always had the same phase relative to the carrier. However, the relative phase was adjustable by a slight change in the tuning of one of the circuits in the frequency multiplier.

Some of the oscillograms taken with this equipment are shown in Fig. 3. In this figure the vertical column of oscillograms on the left illustrates the resultant wave form when the noise wave and the carrier wave are added with various phase angles. The second column illustrates the output of the discriminator for the same conditions. It can be seen that the zero and 180-degree phase angles produce the maximum amount of amplitude modulation and the minimum output from the discriminator. The 90-degree and 270-degree phase angles produce minimum amplitude modulation and maximum output from the discriminator. The intermediate phase angles produce both types of modulation.

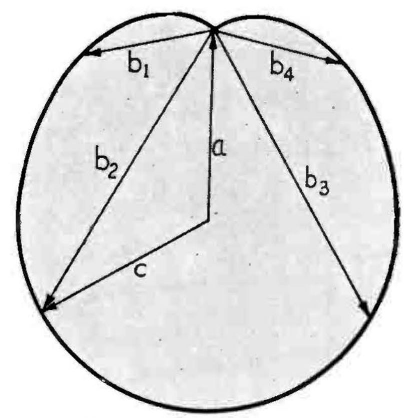


Fig. 6—Vector diagram corresponding to Fig. 5. Signal-to-noise ratio is 0.5. Relative phase is 180 degrees at peak of noise

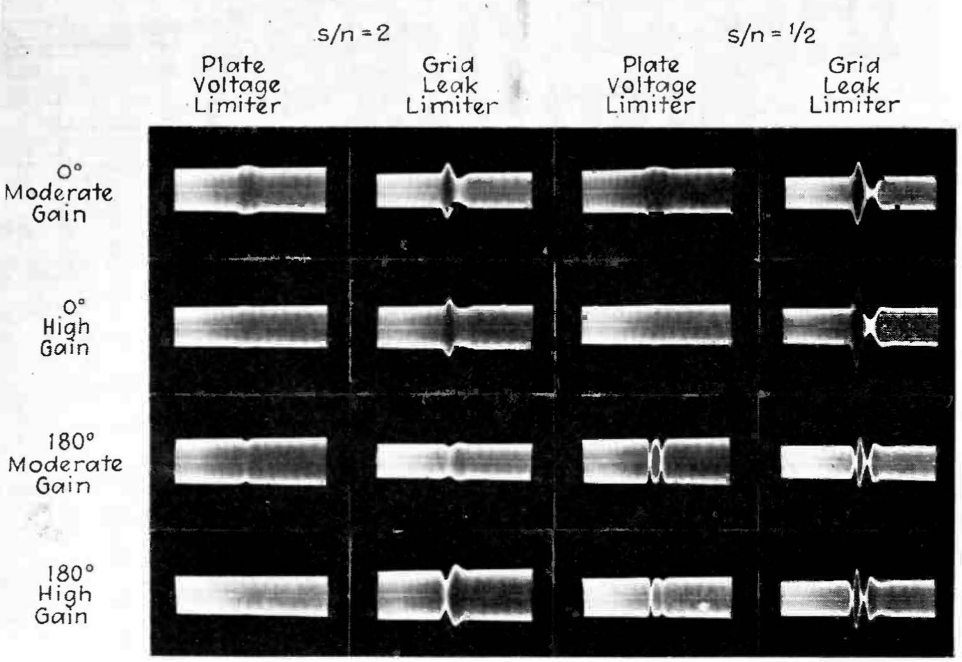
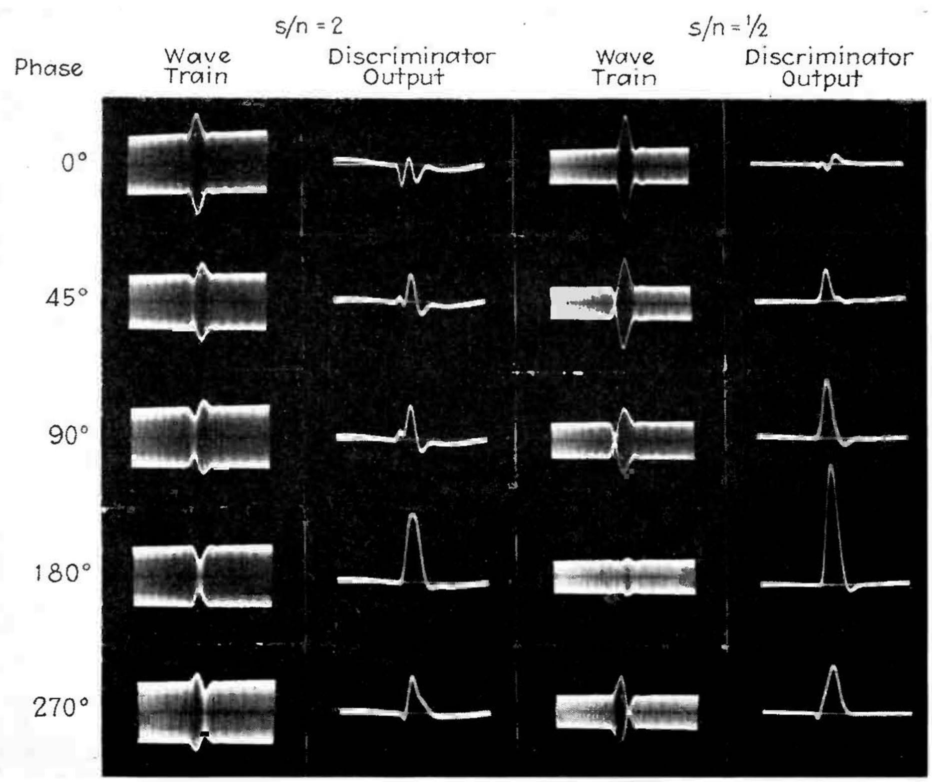


Fig. 4—(above) Oscillograms demonstrating the relative effectiveness of plate voltage and grid leak limiters . . . Fig. 5—(below) Oscillograms of noise and discriminator output with carrier tuned to edge of the pass band



The fact that the 90-degree phase angle produces the equivalent of frequency modulation can be seen by referring to the vector diagram on the left. The vector a represents the carrier wave, the vector b represents the noise wave at the instant of its peak value and the vector c represents the resultant when a and b are added. For the first half of the duration of the noise wave the vector b is growing. For the second half it is diminishing. During the time interval when b is growing, the phase angle between a and c is growing. Since frequency is the rate of change of angle, the frequency of the vector c is low during the growth of b and high while b is decreasing. If b is much smaller than a so that the angle is equal to its sine, then the frequency deviation is proportional to the rate of change of b.

In an amplitude-modulation receiver the output is a maximum for a 0-degree or 180-degree phase angle and the output wave form follows the envelope of the noise wave train. In a frequency-modulation receiver the output is a maximum at a 90-degree or 270-degree phase angle, and the output waveform is the first derivative of the envelope of the noise wave train. It should be noted that the output of the discriminator for 270 degrees is inverted compared to that for 90 degrees.

Columns 3 and 4 in Fig. 3 repeat the same tests except that a different signal-to-noise ratio was used. For columns 1 and 2 the signal amplitude was twice that of the noise. For columns 3 and 4 the signal had half the noise amplitude. It can be seen that with the stronger relative value of noise, the noise shows up as a peak even for the 90-degree and 135-degree phase angles. For 180 degrees the noise bucks out the carrier completely and in addition there is a lobe in which the r-f voltage is 180 degrees out of phase with the carrier. In spite of these differences the output of the discriminator has very much the same waveform for one signal noise ratio as for the other. This may be due to the inability of the audio circuit to follow the higher-frequency components of the true wave form. The fidelity would probably have to be flat to several hundred kilocycles to follow the output waveform accurately.

Fig. 7—Oscillograms illustrating noise reduction by plate voltage and grid leak limiters

Effectiveness of Limiter

Oscillograms of this nature can be used to test the effectiveness of various types of limiters as demonstrated by Fig. 4. In this figure the first column of oscillograms is for a signal-to-noise ratio of 2 and shows the output of a plate voltage limiter. This type limiter obtains the limiting action by using a very low plate voltage. The r-f plate voltage swing is limited to something less than the d-c plate voltage employed.

The first oscillogram of the left-hand column is for 0 degrees phase angle with a moderate amount of gain so that only partial limiting is obtained. For the second oscillogram the gain was increased so that limiter action was almost perfect. The third and fourth repeat the conditions except that the phase angle between signal and noise is 180 degrees. This shows that the plate voltage limiter is a rather good limiter.

The second column of oscillograms is for a grid-leak limiter. This type of limiter obtains the limiting action by allowing the tube to bias itself off as the signal increases in amplitude. It is obviously important to keep the circuit response as fast as possible. For these oscillograms 100,000 ohms and 20 micromicrofarads were used. The other conditions for the second column are the same as for the first. These tests seem to indicate that the grid-leak limiter is not as satisfactory as the plate voltage type. The grid condenser apparently cannot charge up rapidly enough to follow the pulsation. However, it does build up some extra bias during the pulsation, and after it is over, the carrier is attenuated for a short time until the extra bias leaks off.

The third and fourth columns in Fig. 4 repeat the conditions of the

NOISE MUCH LESS THAN SIGNAL

CIRCUIT CONDITIONS	SIGNAL CENTERED **	SIGNAL SLIGHTLY DETUNED
Limiter In, Symmetry Perfect	Good*	Good
Limiter In, Symmetry Poor	Good	Good
Limiter Out, Symmetry Perfect	Good	Poor
Limiter Out, Symmetry Poor	Good	Poor

NOISE MUCH STRONGER THAN SIGNAL

CIRCUIT CONDITIONS	SIGNAL CENTERED **	SIGNAL SLIGHTLY DETUNED
Limiter In, Symmetry Perfect	Good*	Fair
Limiter In, Symmetry Poor	Fair	Fair
Limiter Out, Symmetry Perfect	Good	Fair
Limiter Out, Symmetry Poor	Poor	Poor

* Relative terms apply throughout one table, but not from one table to the other.
** Signal centered for zero discriminator output.

Noise in FM

(*Continued from page* 30)

for a signal noise ratio of 2, with the signal tuned to the high-frequency side of the pass band. This is a duplication of column 2 of Fig. 5 except that the signal is tuned to the opposite side of the pass band.

Column 2 was taken under the same set of conditions as column 1, except that a plate voltage limiter was used. The oscillograms of column 2 represent an appreciable noise reduction over those of column 1. Strangely enough, column 3, which is for a grid-leak limiter, appears to be equally good.

Perhaps it is not quite self-evident that column 2 does represent a noise reduction over column 1. This can be made clearer by referring to Fig. 8.

Frequency Spectrum of Certain Pulsations

In Fig. 8 several forms of pulsation are shown with the corresponding energy distribution curves. The first pulsation is called "unit step." The corresponding distribution curve has its amplitude inversely proportional to the frequency.

If the first derivative of the unit step is taken the result is called unit impulse. It is supposed to have infinite amplitude and zero time duration but it encloses unit area. Unit impulse has the same amount of energy at all frequencies.

If a unit impulse is applied to an ideal low pass filter, the theoretical output is $\frac{\sin 2\pi f_c t}{t}$, which is the pulsation illustrated. The energy distribution is uniform out to the cutoff frequency.

If the first derivative of this pulsation is taken, the result is the pulsation illustrated at the bottom of the figure. The energy content of this wave is directly proportional to the frequency up to cutoff.

It is apparent that many of the oscillograms representing the discriminator output are similar to one or the other of these pulsations. Now the bandwidth of a frequency-modulation receiver is 200 kc, so that from a modulation standpoint the cutoff is 100 kc. The energy content in the audio spectrum is that represented by the shaded area in each case. It is obvious that much less energy is present in the audio spectrum of the pulsation illustrated at the bottom of the figure. One way of looking at it is that the low-frequency components of the wave tend to cancel out if the area in the pulse above the axis is equal to the area below the axis.

Theory of Improvement Due to Limiter

Referring again to Fig. 7, there are several oscillograms in column 1 which do not have equal area above and below the axis. This inequality is almost eliminated in columns 2 and 3, indicating a reduction in the low-frequency energy content. The equalization of area is to be expected from a theoretical standpoint. If the noise amplitude is less than the carrier amplitude, the resultant wave can neither gain nor lose a cycle. If no cycles are gained nor lost, then the frequency must average the same as the carrier. Thus if the limiter takes out amplitude variations in the resultant wave, the output of the discriminator must have equal area above and below the axis. Thus, a limiter does reduce the amount of noise if the carrier is detuned and if the noise is weaker than the signal. When the signal is accurately tuned in, the improvement due to the limiter takes place only on noise pulses which occur while the carrier is deviated from center by modulation.

Recommendations for Improved Performance

From the data provided by all these oscillograms, certain recommendations can be made for improving the performance of frequency-modulation receivers:

1. If the best noise reduction is to be obtained, the selectivity curve must be symmetrical and the discriminator must be accurately centered. More specifically, the overall curve through the discriminator must be symmetrical. The best noise reduction cannot be obtained if the selectivity curve is chair shaped, even if a limiter is used.

2. This symmetry must be maintained for all possible signal strengths. If automatic volume control is employed, consideration must be given to the fact that the input capacitance of the tubes varies with bias. A large enough tuning condenser must be used on the grid circuits to make the change in tuning negligible. If automatic volume control is not used, account must be taken of the change in tuning due to grid current. Large tuning condensers should be used for any tuned circuits feeding grids that are apt to draw grid current. The degree to which symmetry has been maintained in the presence of grid current (or limitation of any kind) can best be shown by a series of oscillograms of the type of Fig. 2. The desired information cannot be obtained by means of a selectivity curve because any lack of symmetry is masked by the limiter action. The apparent selectivity curve taken point by point might appear symmetrical because of the action of the limiter in flattening the top of the curve. Under the same conditions, impulsive noise might come through at a frequency deviating from the center of the pass band, the deviation being caused by grid current which detunes one circuit during high amplitude impulses.

From further tests, not shown here, the grid-leak type of limiter seems to be particularly good in avoiding the detuning due to grid current. In fact, it seems to be the most desirable type of limiter tested, in spite of its apparent inability to remove the amplitude modulation. If Fig. 4 is re-examined keeping Fig. 8 in mind, it can be seen that the grid-leak limiter does remove the low-frequency components from the envelope of the wave. This type limiter may also be used as a source of automatic volume control voltage. It may be used in combination with the plate voltage limiter to obtain still better limiter action.

3. In the output circuit of the discriminator the two sides of the circuit must have the same fidelity characteristics. A good fidelity balance is seldom obtained in practice because the output circuit is usually grounded on one side instead of the center. As a result, there is more capacity across the grounded side than across the high side. The extra capacity can be compensated for, as shown in Fig. 1.

4. From the standpoint of noise reduction the limiter has little value, providing the circuit constants are properly balanced. The limiter helps

to reduce the noise only when the instantaneous frequency of the carrier is off center. If the signal is accurately tuned in, this means that the improvement takes place only on noise that occurs during a modulation peak. Noise which occurs only during modulation peaks is very likely to be masked by the modulation. However, the desirability of a limiter is affected by other considerations than noise reduction. For example, the limiter does reduce the distortion if the selectivity curve is not flat over the 200-kc frequency band. This may make it desirable to retain the limiter. The grid-leak type of limiter seems to be almost as effective for noise reduction as the plate-voltage limiter in spite of its demonstrated inability to remove the amplitude modulation.

A more accurate idea of the degree of usefulness of a limiter can be obtained by referring to Table I. The table at the top of the figure indicates the degree of noise reduction obtainable for relatively weak noise pulses. It indicates that the use of a limiter, and the symmetry of the selectivity curve are unimportant, providing the instantaneous frequency of the carrier wave cor-

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RADIO OPERATORS TRAIN FOR WAR

The signal section of the Royal Air Force gives intensive training to young men born between 1913 and 1920 and who are destined to become radio operators. Here are two students being instructed in modern radio theory and practice at the College of Wireless and Telegraphy in Manchester