Built-in and outdoor antennas for f-m reception, front-end and i-f circuit arrangements, and demodulation systems are discussed in this symposium.* Included is a useful method of testing an antenna by comparing the voltage delivered at the receiver to the voltage obtained from a reference antenna

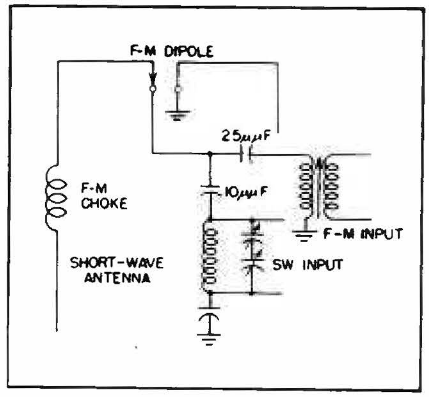
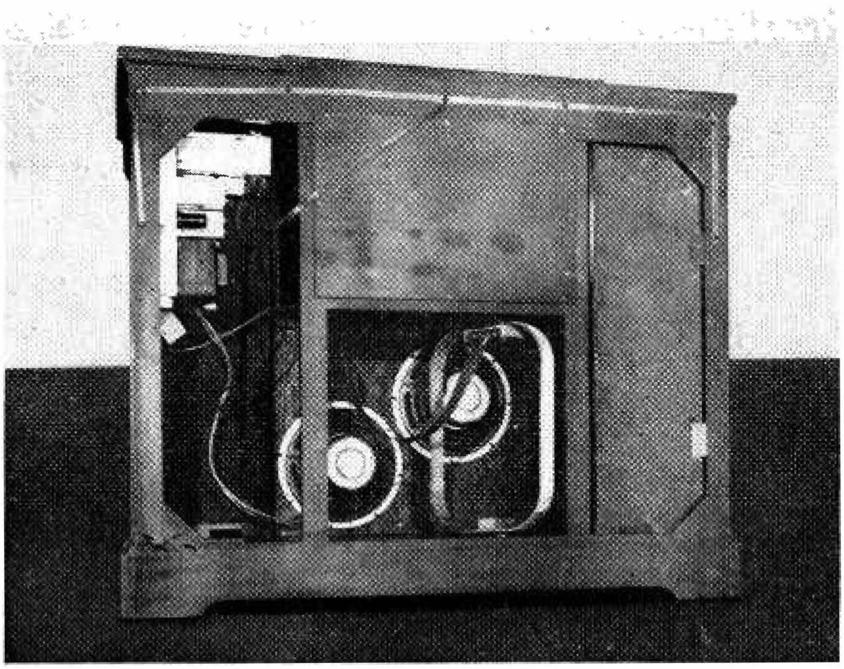


FIG. 1—Simple combination antenna covering one f-m band and short waves

F-M Reception Problems



A simple built-in f-m antenna is a folded dipole made of 300-ohm twin lead and tacked to the back of the cabinet as in this Hallicrafter receiver

THE AVERAGE USER of an f-m broadcast receiver has a right to expect that the installation and operation of his set should be no more complicated than for the standard broadcast set he bought ten years ago.

Since receivers, like population, are concentrated in cities and towns, and f-m transmitters are being located at the centers of these concentrations, f-m coverage is essentially a metropolitan or urban proposition. This means that although some rural areas as well as some outlying towns and villages will be served, the majority of listeners will be relatively close to the transmitters, where high field strengths prevail. For this reason it is feasible to provide built-in antennas in f-m receivers and to expect them to operate satisfactorily in most installations.

Built-in antennas for f-m sets involve some problems that are not found in standard broadcast sets. This is so because the buildings in which the sets are used are large compared with the wavelength. The dimensions of the rooms in which sets are used, and even the dimensions of the radio cabinets, are comparable with the wavelength. Therefore, large standing wave patterns are frequently found to exist, and small differences in the position of the radio set within a room, or even the position of people moving within the room, may make a relatively large difference in the received signal strength.

This means that the performance of built-in antennas is variable, and one type may perform well in a particular location while another type will perform better somewhere else. In most metropolitan locations the signals are strong enough that these problems are completely cared for by the limiter of a sensitive receiver.

Double Antenna

Figure 1 shows one type of built-in antenna. It is a dipole constructed of wire and fitted to the inside of a console. The arms of the dipole are bent or folded so that they will fit into a cabinet of reasonable size. The antenna shown in this figure also includes a length of wire used for shortwave reception. This wire is isolated from the dipole by means of a choke having high impedance to the f-m frequencies and relatively low impedance to the short-wave frequencies. The receiver has separate input circuits

*From papers presented before the Chicago Section and the Indianapolis Section of IRE

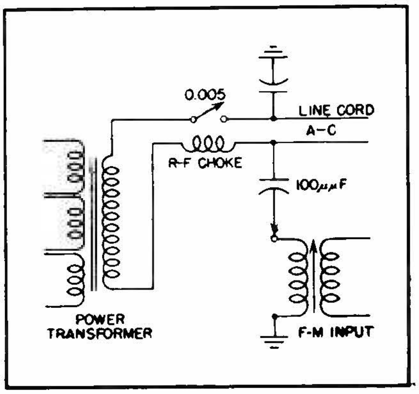


FIG. 2—Circuit for a line-cord antenna suitable for reception of f-m signals

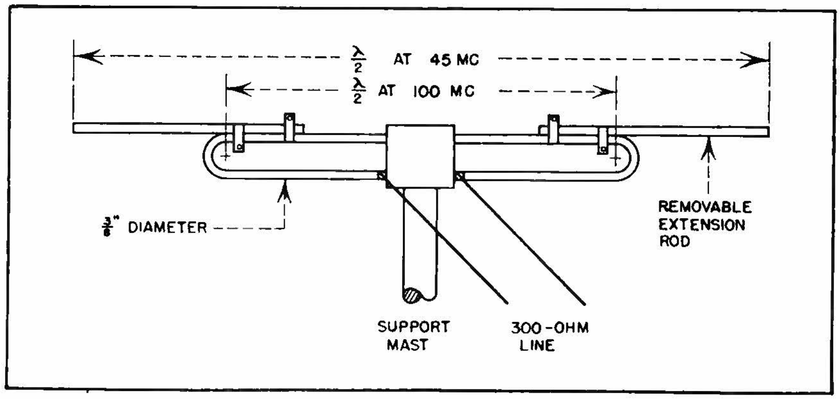


FIG. 3—Mechanical arrangement of antenna elements for reception on both the old and the new bands

and Their Solution

for f-m and shortwave, and these are tied together at the antenna terminals by means of a network which prevents undue loading of one circuit by the other.

Another form of built-in antenna is shown in Fig. 2. This is the familiar line-cord antenna adapted to f-m reception. Since one side of the line cord must be bypassed to reduce line noise in the broadcast section of the receiver, it is essentially the signal voltage between the two conductors of the line cord which is used as input to the f-m circuits.

In some locations the cabinet dipole will work better, and in other locations the line-cord antenna will work better. Since they are inexpensive, both can be provided in a console f-m set and the user may select the one which works better in his location. Table model radios are generally too small to accommodate the cabinet dipole, and for this application the line-cord antenna is preferable. Both of these antennas provide good reception on the low and high f-m bands.

Both F-M Bands

In outlying districts where built-in antennas do not give satisfactory performance, a several-fold improvement may be had by using a simple outdoor antenna with low-loss leadin. Figure 3 illustrates such an antenna which works satisfactorily on both the old and the new f-m bands. This antenna consists of a 100-mc, half-wave folded dipole fitted with extension arms that build up the length to a half wavelength at 45 mc.

The efficiency of the antenna is somewhat better on the low band than on the high band. If low-frequency f-m broadcasting should be discontinued or the band changed, the extension rods can be discarded and the antenna will function with full efficiency on the high band only.

With an outdoor antenna the performance is much less variable than with a built-in antenna. It becomes meaningful to measure the performance and obtain curves showing the effect of frequency over the band in which we are interested. There are several characteristics of antennas that permit critical measurements for the purpose of comparison. For example, it is important in television antennas that the impedance closely match the impedance of the transmission line at all the operating frequencies. This measurement may be expressed by a curve of impedance against frequency, standing-wave ratio of reflection coefficient, or attenuation due to mismatch. Antennas may also be measured in terms of their directional patterns or signal gain.

For f-m service, impedance matching is not a major consideration. It is quite satisfactory to test an antenna in terms of voltage delivered to the receiver. In doing this it is convenient to compare the voltage with that obtained from a standard or reference antenna. The common reference is a resonant half-wave dipole. The setup for making this test may be of interest, and Fig. 4 shows the method used in obtaining a curve for the two-band antenna just shown.

Antennas for F-M Receivers

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Test Technique

Tests are made using the antenna for receiving. At each frequency an arbitrary field is set up by a third antenna connected to an oscillator some distance away. The reference antenna is then adjusted to resonant length, placed in the test position, and the voltage V_1 delivered to the matched load is noted. The reference antenna has an impedance of approximately 70

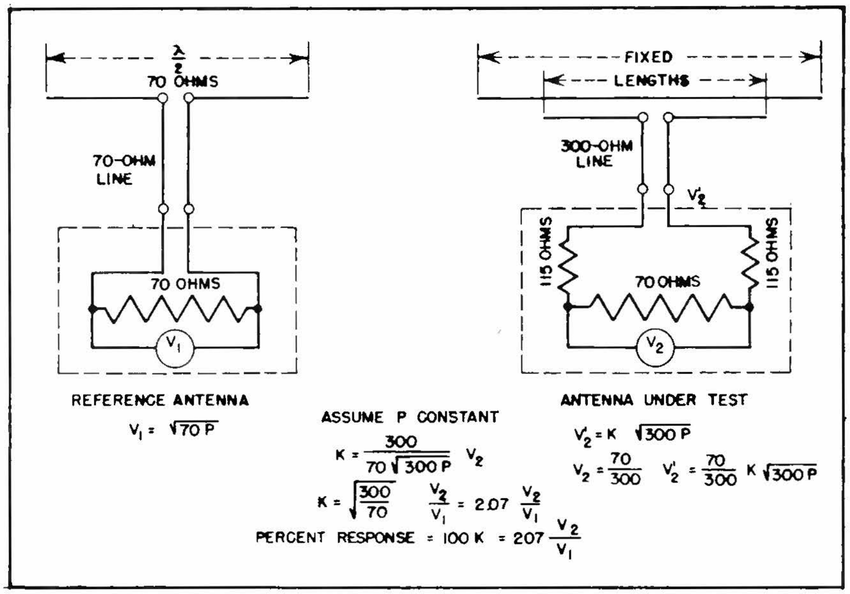


FIG. 4—Method of comparing the two-band antenna against a resonant dipole

ohms, the transmission-line characteristic impedance is 70 ohms, and the load impedance is 70 ohms. The load consists of the input attenuator of a field intensity meter.

The antenna under test is then substituted for the reference antenna at the test position. Since the receiver for which this antenna was designed has an input impedance of 300 ohms, 300-ohm transmission line is used and the field intensity meter input is built up with resistors to match the 300-ohm line. When this is done the field intensity meter input circuit duplicates an ideal receiver input, but the voltage indicated by meter V_2 is equal to only 70/300 of the voltage delivered to the receiver.

By comparing readings V_1 and V_2 of the field intensity meter, the performance of the antenna under test is related to the performance of the standard antenna. Here it is assumed that the power delivered to the receiver by the standard antenna is the maximum power available from the antenna under test, and the fraction of the available power actually obtained is a figure of merit for the antenna. Since receiver measurements are made in terms of voltage rather than power, it is the square root of this figure or the voltage ratio K which is actually used.

After this measurement has been made at a number of frequencies, a performance curve can be plotted. This is shown in Fig. 5. In judging this curve, it should be borne in mind that the reference antenna has been readjusted in length for each frequency. Plotted in this same manner, a simple dipole of fixed length would show considerable selectivity while a simple folded dipole would be relatively broad and comparable to the low-band performance curve shown. If the extension arms of the two-band antenna were removed, the high-band curve would look very similar to the low-band curve as plotted, but the low-band curve would suffer seriously.

Experience indicates that built-in antennas of the line-cord and cabinet dipole types give satisfactory set operation at practically every location in the Chicago metropolitan area on either the low or high bands. At distances of about forty miles, a simple outdoor antenna becomes useful in many installations; and at greater distances, approaching the nominal service area limit, the outdoor antenna is required in all but exceptionally good locations.

R-F and I-F Circuits

In considering the circuit elements between the antenna terminals and the output of the i-f amplifier, it must be noted that the best distribution of gain in an f-m receiver is determined largely by noise considerations. A certain amount of noise is produced by thermal agitation in the antenna circuit. If the maximum signal-to-noise ratio is attained in the antenna circuit and the amount of noise added in later stages is very small compared to that in the antenna circuit, the signal-to-noise ratio of the receiver can be made to approach (as a maximum) the ratio established in the antenna circuit.[1]

The maximum antenna stage gain is $0.5\sqrt{Z_t/Z_1}$ where 0.5 accounts for matching to the source impedance; Z_t is the impedance into which the antenna transformer works, and Z_1 is the source or transmission-line impedance. It is assumed that the impedance of the secondary of the antenna transformer is considerably greater than the input loading of the tube, which is usually the case, in a receiver using an r-f stage.

Input Stage

The r-f amplifier tube is chosen primarily on the basis of low input conductance, low noise, fairly high mutual conductance, low grid-to-plate capacitance, and low cost. In an a-m/f-m receiver, signal-handling ability with avc applied may be an important consideration. Since these factors are not combined in any single tube, the final choice represents a compromise.

The maximum stable r-f stage gain in a variable-capacitor tuned stage having a solid rotor shaft is about 10 times. If the antenna and r-f circuits are isolated from each other as in permeability-tuned receivers, somewhat greater r-f stage gains can be safely realized.

The amount of r-f stage gain required depends upon the relative amounts of noise at the r-f tube grid and the mixer grid. If the same type of tube is used as r-f amplifier and converter, the mixer tube noise voltage is approximately two times the r-f amplifier tube noise. To avoid any substantial decrease in the signal-to-noise ratio, therefore, a gain greater than five times is required in the r-f amplifier stage.

The noise voltage developed in a mixer tube depends largely upon the type of tube used and its mutual conductance. Of the commonly used types of mixer tubes, the pentagrid converter is the noisiest, the pentode is less noisy (and frequently a good compromise) and the triode is the quietest. The diode, and better still, the crystal mixer, are extremely quiet; however, stage gains less than unity are common using these mixers, and a quiet first i-f stage amplifier tube is required if either is used.

The oscillator stability and tuning accuracy requirements for an f-m receiver are considerably greater than for an a-m broadcast receiver. The a-m receiver must be tuned within about ±2 kc in a 1,000-kc band (or the dial must be set to about ±0.2 percent) if noticeable distortion is to be avoided. The f-m receiver must be tuned within about ±20 kc in a 20-mc band, or about ±0.1 percent. The oscillator must be stable to within about two parts per thousand in the standard band, and to about two parts per 10,000 in the f-m band.

AFC Circuit

The nature of the oscillator stability and tuning accuracy problems make the use of automatic frequency control on the f-m band attractive. If the oscillator and mixing functions are performed in separate tubes, afc can be provided by adding a few resistors and capacitors, and by using a dual-triode tube as the oscillator and reactance tube. Such a system is used in several Hallicrafters home receivers.

A circuit of this type is shown in Fig. 6. The plate of the oscillator is capacitance coupled to the grid and plate of the reactance tube. The resultant voltage on the grid of the reactance tube is shifted in phase approximately 45 degrees by resistor R_1, capacitor C_2, and the capacitance from the reactance tube grid to ground. This voltage is then amplified by the reactance tube according to the value of direct voltage on its grid and appears as a current in the oscillator plate feedback winding, shifted in phase from the oscillator plate current by about 135 degrees. The d-c component of the output of the frequency detector can be used as the control voltage applied to the grid of the reactance tube.

The slope of the reactance-tube characteristic can be adjusted so that the afc system takes hold and releases within the frequency limit of the next adjacent local channel (400 kc), and a correction of about five to ten times on the oscillator mistuning can be realized. Under these conditions, the afc operation prevents the receiver from reproducing the two spurious responses, which occur on each side of the desired response points in a receiver without afc.

I-F Amplifier

The i-f amplifier in an f-m receiver is required to produce a major part of the total gain and the selectivity of the receiver. The selectivity is usually made as great as possible without harmful effects upon the signal; that is, when the f-m signal swings back and forth on the curve of the i-f selectivity characteristic, the result is amplitude modulation. The limiter or detector must be able to remove this a-m and restore the signal to its original form to avoid distortion in the audio output. At the same time, a small amount of phase distortion is produced due to the nonlinear phase characteristic of the i-f amplifier when the sidebands of the signal are too far from the center frequency in terms of the bandwidth of the amplifier. As a practical matter, the amplitude variations in a typical i-f amplifier are far more troublesome than the lack of linearity of the phase characteristic.

In the most popular design for i-f amplifiers, the bandwidth of the amplifier is made about equal to the total deviation. This seems to include an adequate allowance for error in tuning, oscillator drift, and other factors in a well designed receiver. Each i-f transformer consists of a pair of tuned circuits coupled to slightly less than critical coupling, so that normal variations in coupling can be allowed in production without some transformers being over-coupled.

It is the usual practice to make the Q of the primary equal to that of the secondary, since the passband is too narrow to allow any appreciable improvement in gain with practically obtainable ratios of Q. Moreover, unequal values of Q for the primary and secondary cause

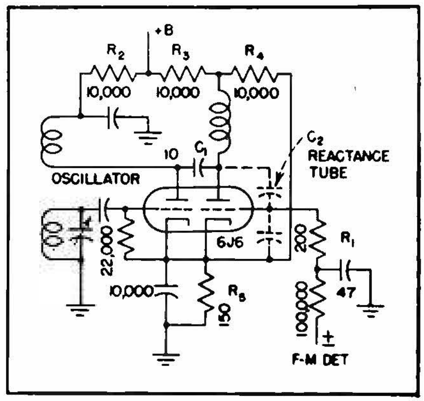


FIG. 6—A tuned-grid oscillator and afc reactance-tube circuit

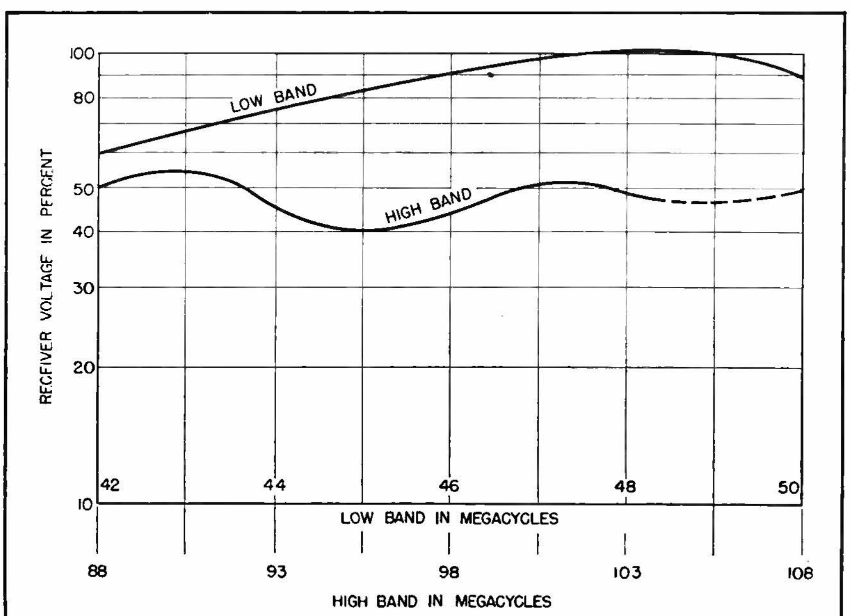


FIG. 5—Receiver voltage for a two-band antenna with 300-ohm line feeding into a 300-ohm input compared with a matched-impedance resonant dipole

asymmetry of the amplitude and phase characteristics when either primary or secondary is detuned relative to the other circuit.

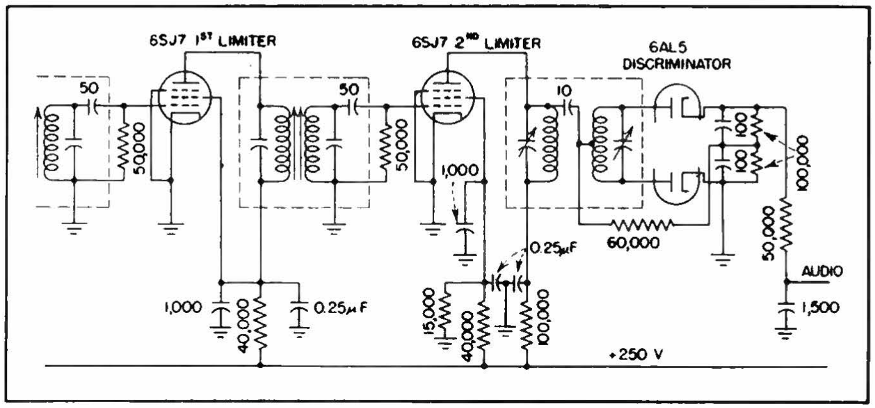
The gain of the i-f amplifier is usually made as high as cost and stability considerations will permit. If maximum sensitivity is to be realized, an optimum value seems to be enough gain to assure saturation of the limiter (or a comparable noise value at the ratio detector). This allows satisfactory reception of any signal which is of sufficient intensity to overcome the noise voltage at the limiter or ratio detector. A margin of about 10 db over the i-f gain required to produce this saturation by noise is needed to insure maximum performance under all conditions.

Maximum stable stage gains may be computed by means of a formula given below.[2] It is usually advisable to limit the stage gain to somewhat less than one-half of the calculated value for safety.

$A = \sqrt{\frac{g_m}{\omega C_{pg}}}$ (multiply A by $1/\sqrt{n}$ for n stages) where A = maximum stage gain, g_m is in micromhos, ω is in radians per second, and C_{pg} is the effective plate-to-grid capacitance in farads.

High-Capacitance Grid Circuit

There is one departure from conventional i-f transformer design that has been developed recently. The usual value of tuning capacitance on an i-f transformer primary or secondary is about 50 $\mu\mu f$ or less. The input capacitance of the commonly used tubes varies about 2 $\mu\mu f$ when the grid voltage is varied from the normal bias value to cutoff. This means that impulse-noise voltages on the last i-f amplifier tube or limiter tube can produce detuning of the i-f transformer secondary, and thereby introduce phase distortion in the signal. The limiter removes most of the amplitude modulation of the carrier due to the noise pulse, but it cannot remove the phase distortion. Remarkable improvements in signal-to-noise ratio have been reported when the secondary tuning capacitances in the last i-f and limiter grid circuits were increased.



Receiver circuit with a double limiter and a discriminator. Capacitor values in $\mu\mu f$ unless otherwise noted

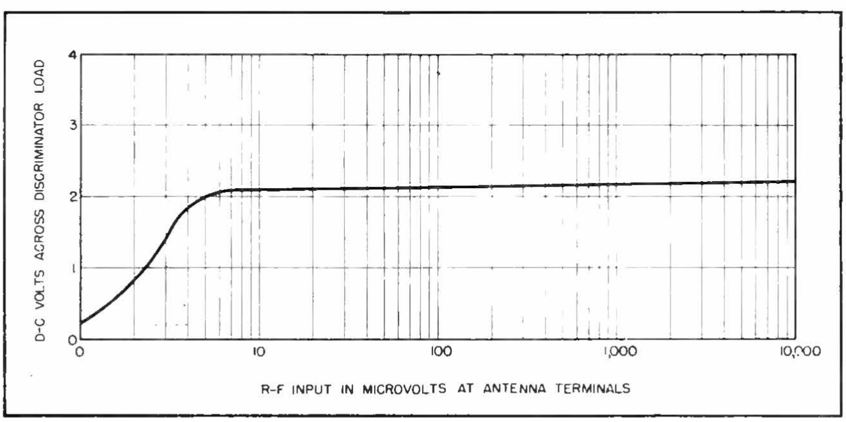
The gain of a double-tuned i-f stage is inversely proportional to the square root of the product of the values of the tuning capacitances. This suggests that, since the tube output capacitance is substantially constant, the stage gain obtained from a symmetrical transformer can be duplicated with only the output capacitance and strays tuning the primary, and the secondary capacitance increased by the same ratio by which the primary capacitance was decreased. It is desirable to keep the Q of the primary equal to that of the secondary.

Three types of wide-band f-m detector systems have appeared in production receivers since the war, namely—the limiter-discriminator combination, the ratio detector and the locked-in oscillator. For practical considerations, it seems best to evaluate these systems in terms of the overall performance of the various receivers in which they are employed. However, the detector is often blamed unjustly for the poor performance of receivers in which cost considerations have led to sacrifices throughout the complete circuit. All of the systems mentioned have certain disadvantages as well as their own peculiar advantages. Any of above systems can be made to perform quite satisfactorily.

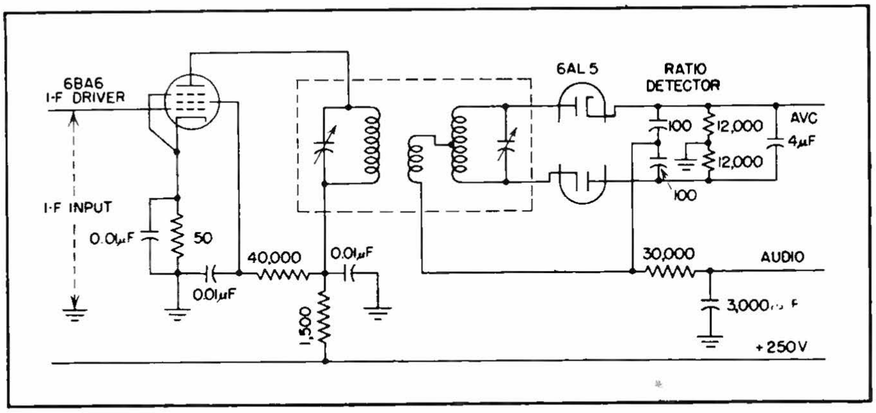
The Limiter-Discriminator

It has become customary to employ two grid-plate limiters in cascade in the more elaborate receivers using this system. The parameters for each limiter are adjusted so that the maximum range of linearity without appreciable change of output level is realized. Grid circuit constants are chosen to provide a low time constant for optimum limiting of impulse noises.

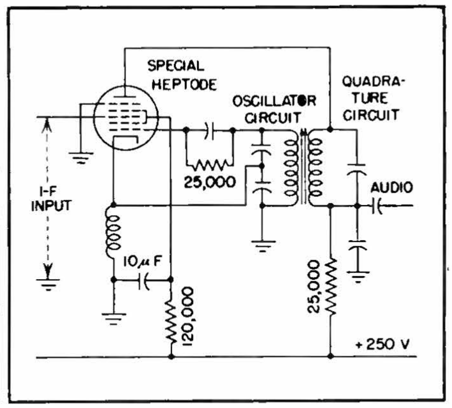
Since adequate gain must be provided ahead of the limiters to realize full action at low antenna input levels, they are usually preceded by two i-f stages, a mixer, and one r-f stage, preferably with separate



Input-output characteristic of a sensitive limiter-type receiver which shows that practically flat response may be obtained without the use of avc. The long flat portion at high signal levels indicates ability to handle downward modulation. Curve obtained with carrier deviated ±50 kc from center frequency of detector



Ratio detector system for an f-m receiver employing a transformer having a tertiary winding



Simplified circuit of the lock-in oscillator and quadrature detector combination

tubes to furnish maximum gain. Lower priced receivers often employ a single limiter, which results mainly in a loss of overall sensitivity and a limitation of the range of signal levels over which amplitude modulation is fully suppressed.

The main factors considered in the selection of proper constants for the discriminator include an adjustment of the primary to secondary coupling and circuit Q to provide the optimum degree of linearity throughout the working range of the detector. Circuits employing either variable capacitance or variable inductance tuning have been developed.

The limiter-discriminator combination has the advantages of being unaffected by modulation variations within the operating range of the limiter and of being relatively noncritical in so far as discriminator linearity and balance are concerned. It has the disadvantages of requiring a high gain before the limiter and of a broadening selectivity characteristic with increasing signal level.

Ratio Detector

Due to the inherent ability of the ratio detector to suppress amplitude modulation at comparatively low input levels, it offers a desirable opportunity to those who wish to incorporate reception facilities at a minimum cost. This characteristic is particularly advantageous in those receivers employing common r-f and i-f amplifier tubes for both the a-m and f-m channels and has led to the production of complete a-m/f-m receivers incorporating as few as seven tubes. If the ratio detector is properly designed these receivers can provide acceptable performance. Unfortunately, many of them do not suppress amplitude modulation or provide low distortion levels.

One chief requirement for the proper suppression of amplitude modulation is careful balancing of the two diode circuits. The use of bifilar secondary windings of high Q and a proper choice of circuit constants can produce very beneficial results in this respect. The required linearity for low distortion is not difficult to obtain with a well balanced circuit, but many production sets suffer due to excessive selectivity ahead of the detector. The i-f selectivity often varies due to regeneration or coupling coefficients not controlled in low-cost receivers, resulting in high downward modulation during wide frequency swings and considerable distortion.

These difficulties with the ratio detector can be overcome provided a careful design is made and a high degree of quality control is exercised in production. The chief advantage of the system is its ability to suppress amplitude modulation at lower signal levels than is possible with limiter sets.

The main disadvantages are the problem of handling high percentages of downward modulation, produced by multipath signals and excessive selectivity, and the fact that avc voltages must be applied to several high-frequency stages with the possibility of shifting their tuning and the symmetry of the selectivity characteristic.

These disadvantages can be overcome to a great degree if the audio output requirements for the detector are reduced and provided enough i-f stages can be employed to allow the use of high grid circuit capacitances in the amplifier circuits which are automatically biased.

Locked-in Oscillator

The locked-in oscillator operates in a manner similar to the double limiter arrangement throughout the lock-in range of the oscillator, but it may distort badly when the signal level drops below the lock-in threshold. It has been employed by one manufacturer commercially and in several forms experimentally, such as the use of a submultiple oscillator to convert to narrow band f-m before detection and the use of combined oscillator-detector circuits.

In general the advantages and disadvantages are of the same general nature as those of the limiter system. An important consideration is the necessity for eliminating any extraneous frequency or phase modulation of the locked-in oscillator by filament, screen or plate voltage variations.

The locked-in oscillator has the inherent capability of being less susceptible to interference than any of the three systems described, but practically its entire performance depends on the degree to which the oscillator can stay ideally locked to the desired signal.

References

(1) E. W. Herold, An Analysis of the Signal-to-noise Ratio of Ultra high-frequency Receivers, *RCA Rev.* 6, Jan. 1942; D. O. North, The Absolute Sensitivity of Radio Receivers, *RCA Rev.* Jan. 1942.

(2) J. R. Nelson, *Proc. IRE*, Feb. 1929.