A RECEIVER FOR FREQUENCY MODULATION

The first published data for the construction of an f-m receiver. Using but seven tubes, the circuit displays a sensitivity of the order of 5 microvolts, is flat from 30 to 15,000 cps within 2 db, and may be constructed from standard components

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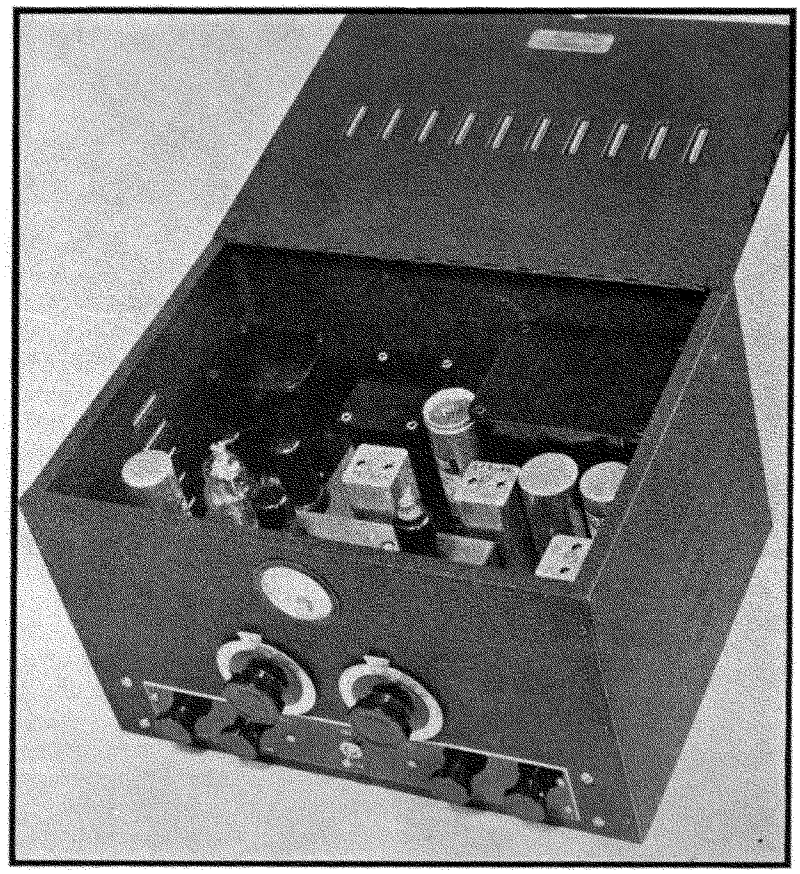
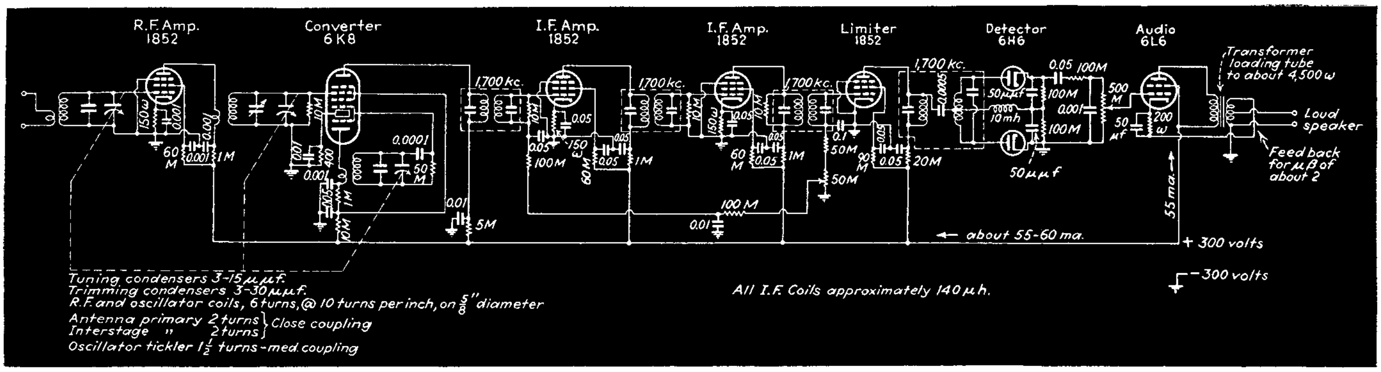
THE frequency-modulation receiver described here is representative of many others, some more elaborate, and some more simple. It was selected because its design and construction embrace all the features that distinguish frequency modulation receivers from amplitude modulation receivers. This receiver has proved capable of rendering noise-free and high quality audio from very small signals, corresponding to a field strength of from one-tenth to one one-hundredth the value that would be necessary in the case of amplitude modulation, in the absence of outside interference, and in addition possesses the advantages relating to the suppression of noise originating outside the receiver that have been demonstrated for wide-band frequency modulation.



A commercial type of f-m receiver constructed by the Radio Engineering Laboratories using the same tube complement as that described by Mr. Day, but with a somewhat more elaborate audio system

At the outset it might be well to recall a few generalities. A frequency-modulated wave is a radio-frequency carrier wave whose frequency is caused, at the transmitter, to vary linearly above and below its nominal value in accordance with the desired modulation. It is also a distinguishing and important feature of Major Armstrong's method that the maximum deviation of the transmitter frequency is several times the value in cycles of the highest frequency present in the modulation. The transmitter output, during modulation, therefore covers a considerable bandwidth, and the receiver must be designed to handle it adequately. Transmissions at present use a maximum deviation of ± 75 kc. The receiver described here when properly aligned will handle such a transmission with negligible amplitude and frequency distortion.

The block schematic diagram shows that the antenna current is received at a high frequency, is amplified, converted to a lower intermediate frequency, amplified further, passed through a current limiter, converted to amplitude modulation, and finally demodulated. Since the magnitude of the recovered audio is a function of the time rate of change of the frequency of the carrier current it follows that, unless the phase shift of the various circuits up to the detector is linear, there will be amplitude distortion. It is not hard to keep the distortion due to this to less than 1 per cent of the peak amplitude of the recovered audio, with thoroughly practical values of the circuit parameters. Observing this precaution the amplification from antenna to current limiter grid may be increased or decreased as necessary or convenient, only providing that there is sufficient gain at all times to provide adequate limiting action in the limiter stage. The receiver of the circuit diagram



Complete circuit diagram of the receiver. I-f transformers for 1700 kc are now available commercially and may be modified readily for wide-band reception

represents a middle ground in the way of sensitivity, and the values given are merely for the purpose of guidance, at the frequencies indicated.

The two tuned circuits at 7 meters do not provide a very high image ratio with an intermediate frequency of 1700 kc. However, consideration of the results shown by Weir will disclose that the requirements here are less stringent than would be the case were this receiver for amplitude modulation. The two r-f circuits and the oscillator in this case are operated from a single control, but for the purposes of an experimental receiver a separate control for the beating oscillator, enabling tuning both above and below the carrier frequency, would naturally give greater flexibility. Also the use of a higher intermediate frequency would better serve circumstances requiring a higher image ratio. The measured image response ratio of the receiver is about 18-to-1. Naturally the Q of the r-f coils is low enough to insure linear transmission and phase shift over the range of ± 100 kc. The resistor loading the grid of the 6K8 type tube was put there only because a wide variation in the input resistance at 40 megacycles among tubes was experienced. It appears that the new 6SA7 type is somewhat better in this respect. Some regeneration in the r-f section can be tolerated provided it does not unduly sharpen the transmission characteristic. The step-up in the antenna coil is about 5, and the gain of the 1852 stage to the converter grid is 12. At the time it appeared the 6K8 type offered advantages in stability at high frequencies that governed the choice. The 6SA7 now appears to be superior in this respect also.

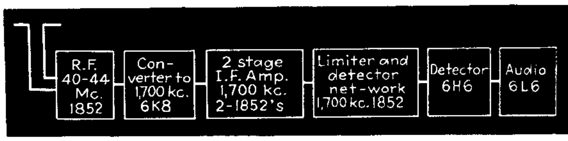
Frequency modulation of the oscillator voltage is particularly to be avoided. This may occur in a variety of ways including plate supply ripple, tube, coil, and condenser microphonic response, and heater-cathode leakage in the case where the cathode is above ground. Ripple frequency filtering in the plate supply, rigidity of coil and condenser, microphonic isolation of the tube, and large d-c bias from heater to cathode will ordinarily remedy these ills. In bad cases it may be found desirable to by-pass, and perhaps filter, the heater leads for r-f at the socket. Chokes (very small) of about 5 microhenries and 0.001 microfarad condensers will fill the bill nicely. It should be pointed out that these effects are generally very small and would not be appreciable if the overall reproduction were not so uncommonly quiet. The conversion gain of the stage is about 4.

The intermediate frequency amplifier is perfectly orthodox, and can probably be considerably improved. The 1852's give a gain of approximately 70 per stage. A gain of 50 per stage would materially lessen the hazards of unwanted feedback. Ready-made double-tuned i-f transformers are available to the trade for quite a variety of high intermediate frequencies. Several of these can be modified very simply to conform to the needs of this receiver. The coils used here were of 140 microhenries inductance and the necessary bandwidth obtained by manual adjustment of the coil spacing on the dowel, in conjunction with the indicated loading. In this case the coils were small universal-wound units of about 3/32 inch width, and the optimum coil spacing is about 3/8 inch between centers.

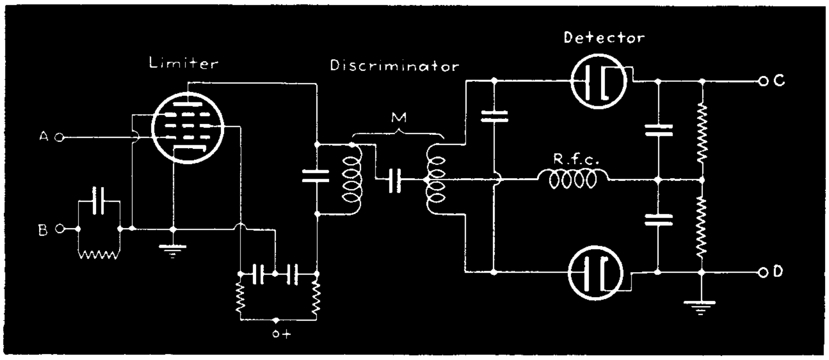
The sensitivity of the receiver cannot be compared directly with the sensitivity of an amplitude-modulation receiver, for obvious reasons, but it is possible to state a minimum signal level, required at the input of the frequency modulation receiver, to produce adequate limiting action. A voltage level of about 6 volts is required at the grid of the limiter tube to insure proper limiter action. The gains per stage prior to this grid are, from the antenna coil inward, as follows: 5, 12, 4, 70, and 70, or a total of 1,100,000 times. Accordingly, a six-volt signal can be developed from a minimum input of between 5 and 6 microvolts. It should be noted that this is the minimum signal required for limiting action against the effects of external noise. If there is no external noise to contend with, the discrimination against tube noise is active even with signals as weak as a fraction of a microvolt.

The resistance loading on the i-f coils performs a number of related functions. As mentioned before, the variation of phase angle with frequency of each coupling circuit should be linear for an interval above and below the carrier equal to the maximum frequency deviation in the transmission. A conservative figure is ± 100 kc for transmissions swinging ± 75 kc, and would represent a limit of "over-designing" beyond which there would be no benefits. In the absence of elaborate equipment for measuring the phase angle, and in the absence of the stamina required to compute it, a cheap way to

Block diagram of the receiver shown above. Except power supply, but seven tubes are used



insure success is to put one's faith in the old adage that for symmetrical circuits the phase shift is linear over the range where the transmission is constant. As a guide the individual i-f stages should be adjusted to be symmetrically tuned and to be down 1 db at the edges of the band. Symmetry is important, as stagger tuning brings in some rather unpredictable factors and can easily make a graph of the phase angle look like a bed-spring—to say nothing of what the recovered audio can sound like. The resistance loading shown is of course instrumental in obtaining the desired "steady-state" transmission characteristic. It does something else of equal importance. Since the coupling circuits contain *L*, *C*, and *R*, and the currents carried are varying rapidly through the resonant frequency of the combination, transient or free-oscillation currents result. The character of these currents and their harmfulness as spurious responses is controlled by the ratio *L/C* and by *R*. The higher the damping produced by *R* the less pronounced will be this response. In amplifiers handling frequency modulated currents it is important that this transient current be kept to a certain low level and that it be rapidly damped out, for the highest modulation frequencies of importance (this phenomenon is clearly of greater significance the higher the modulating frequency). Using sine-wave modulation, distortion in a frequency modulation receiver due to non-linear phase angle and related defects will be characterized by the usual types of wave malformation. But this second type of distortion will appear very plainly as a damped transient of a short initial period superimposed on each half-cycle of the recovered sine-wave. The transient does not change greatly as the audio frequency is raised, being mainly dependent on the circuit rather than the precise nature of the exitation, and hence is a comparatively greater disturbance to a high frequency modulation wave than to a low. This and related phenomena are described and analyzed by Roder and by Carson and Fry. The equivalent damping shown for the circuits of this receiver is ample to insure freedom from these effects. Reasonable departure from the limits and values given here will not cause aurally detectable distortion, and experience will show the experimenter that the specifications given in this description are safe by quite a margin.



Limiter, discriminator and detector circuit, in which the essential demodulation functions of the receiver are performed

The current limiter amplifier is a coupling stage intended to remove from the carrier variations in amplitude, and to excite the conversion network with a current varying only in frequency and phase. There are a number of ways of doing this, none of them perfect. The circuit will begin to "limit" with an r-f input of three volts peak, will have leveled off at five volts, and will "drive down" slightly as the input is increased to 100 volts. This "driving down" is due to plate and screen voltage regulation as rectification occurs. As operated, this limiter is a grid-cathode rectifier and hence develops a voltage negative to ground on the resistor from coil to ground in the grid circuit. This voltage may be used for avc or manual r-f gain control by applying a part of it to one or more amplifier grids. It is important, though, not to use such a gain control voltage to an extent that might endanger the efficacy of limiting, as exemplified by a limiter grid driving voltage of say 7 volts minimum. The voltage across this resistor or the current in it may be used as a very broad tuning indicator, and, if the stages preceding the limiter are linear, as a measure of the signal strength. It is convenient to note here that up through the limiter circuit there are no requirements whatever on the linearity with amplitude of any of the amplifier circuits. Although this property in the receiver does not permit the economies that it allows in the transmitter it is none the less attractive, and neatly removes one headache for the designer of a high-quality receiver.

The network effecting the change from frequency to amplitude modulation, for the purpose of recovering the audio by ordinary means, is in the plate circuit of the limiter and consists of the familiar discriminator device as used in some types of automatic frequency control. The analysis of this circuit is ably given by Roder. Here again the coupling must be relatively "tight", in order that the peak separation should comfortably exceed the maximum frequency deviation. The circuit as shown for 1700 kc uses coils of 140 microhenries inductance, coupled a bit more tightly than the amplifier coils, that is, for a peak separation of about 250 kc. The diode load shown is sufficient to preserve linearity over the operating range. It will be found that, when the coupling is adjusted, the primary trimmer affects mainly the symmetry above and below mid-frequency of the peaks, while the secondary trimmer mainly affects the cross-over, which should be accurately nailed to the center of the i-f channel. The recovered audio when the tube ahead is limiting will be found to be between 20 and 80 volts peak for a transmitter swing of $\pm$ 75 kc. The operating conditions of the limiter tube for the most part determine the maximum audio output of the detector as shown. It should be noted that the detector output voltage consists of the sum of two voltages, one from each diode. This is a true push-pull effect, and is of aid in balancing out any unwanted modulation that appears on the diodes in the push-push sense. A 6B8 type tube can be used as a combined limiter detector, but it necessitates a grounded common cathode and shunt diode loads, and hence a two-grid audio input. Also, being a remote cut-off tube, it has a somewhat higher limiter threshold. Since the average value of the voltage across the two diode loads in series is zero when the carrier is exactly in tune, and goes positive and negative for deviations from "in-tune", it makes a convenient and accurate tuning indication. A center set voltmeter of sufficient resistance to avoid loading the diodes unduly makes a suitable indicator.

The resistance capacity combination intervening between the diode load and the audio volume control is a so-called "restorer", and is for the purpose of equalizing the present transmission characteristic. At the transmitter the highs are accentuated in the manner familiar as predistortion. This results in a high signal to noise ratio in the high audio frequencies, and for the case of frequency modulation does so without sensibly increasing the danger of side-channel interference. Further, in a frequency modulated system, the random noise voltage per fixed frequency interval increases as the mean frequency. Therefore the net advantage accruing is greater for the frequency modulated than for the amplitude modulated system, where the noise energy per interval is sensibly constant as the mean frequency is varied.

The recovered audio in this receiver is large enough to drive one 6L6 to full output even with the indicated feedback (mu-beta of 2.14 at 400 cycles), and the loss in the restorer. The single 6L6 will turn out 6 watts of single frequency with very low distortion. The high quality afforded by the system and the receiver permits the use of a high listening level without aural distress. However, the full use of even this single tube output will endanger the average apartment dweller's relations with his neighbors.

The writer earnestly hopes that experimenters will do their listening with this type of receiver using good loud-speaker equipment. The electrical fidelity from modulator input at the transmitter to voice coil at the receiver, in the case of this receiver and many others like it, is good to within 2 db from 30 to 15000 cps, with single frequency distortion not exceeding 2 per cent rms for full modulation. Obviously, it would be unfair and wasteful to use poor loudspeaker equipment with such a device.

The most precise method of aligning and testing a receiver like this is a point by point procedure. With a signal from some suitable generator on the grid of the limiter tube, and a high resistance d-c voltmeter across the diode output, the discriminator transformer is tuned so that for constant voltage on the limiter grid the voltage across the diodes varies linearly through zero at mid i-f range from 75 kc above to 75 kc below. It is desirable to keep the peaks as close together as is consistent with linearity in the ± 75 kc range.

The next step is to put a milliammeter in series with the limiter grid resistor and, working back stage by stage with a signal generator, to adjust the coil couplings, loads and tuning until the transmission characteristic of each stage and of all in cascade is symmetrical and flat across the operating range. It will be found that a symmetrical amplifier that is flat for the operating range to within ± 1 db, and that is sufficiently damped, will transmit a frequency modulated current of total deviation equal to the range with virtually perfect freedom from distortion. It is possible to compensate double-peaked circuits by single-peaked circuits, in the usual way, provided symmetry and freedom from feedback are maintained, in such a manner that no appreciable distortion will occur. However, since the action then occurring can be quite complex and is not easily subject to analysis, this method is not generally to be recommended. It is important to bear in mind the nature and origin of the two types of amplitude distortion mentioned above during the lining-up process.

A wide-swing frequency modulated oscillator with provision for a low-frequency saw-tooth sweep will provide a quick visual method of alignment of all circuits. For experimental purposes there are, however, some drawbacks. In the first place, relatively careful calibration of frequency deviation is necessary. The visual accuracy of cathode-ray tube indications is limited. And, finally, there is a strong temptation when using this sort of equipment to align the receiver "over-all" and perhaps unwittingly to indulge in interstage compensation for the sake of a smooth looking transmission characteristic. If this method is used the voltage on the limiter grid resistor (with by-pass reduced so as to shunt out only r-f) is convenient for vertical deflection when aligning the i-f stages and converter.

The alignment of the r-f section consists of simple peaking, as the coil and tube damping are more than enough for the purpose. Although the sensitivity of the receiver is high, and the natural noise-reduction inherently good, a good dipole with associated transmission line will repay the effort. There is nothing out of the run of ordinary short-wave practice in the collection of the signal. Only under very unfavorable circumstances and at considerable distances from the transmitter are special devices such as reflectors, indicated.

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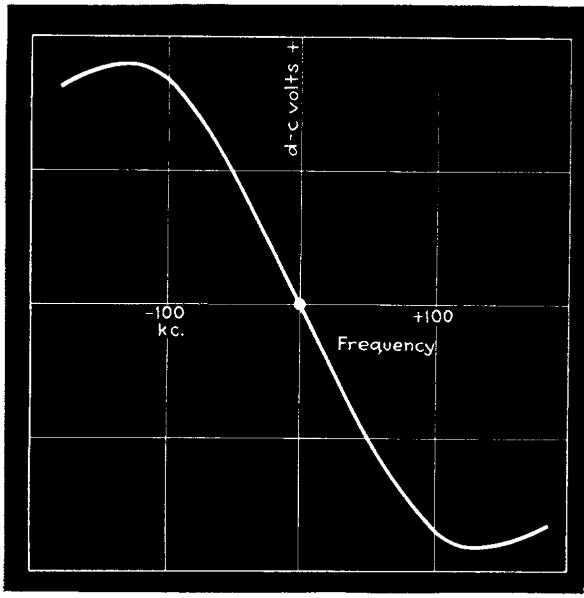

Operating characteristic of the discriminator circuit shown opposite, showing audio output amplitude against frequency deviation