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NRL REPORT R-3460

FR-3460

INVESTIGATION OF NONLINEAR RECEIVING CIRCUITS UNDER TWO-SIGNAL CONDITIONS

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INVESTIGATION OF NONLINEAR RECEIVING CIRCUITS UNDER TWO-SIGNAL CONDITIONS

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November 1949

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CONTENTS

ABSTRACT

This report is a study of nonlinear circuits under two-signal conditions, with particular stress on the output spectral components generated, and on signal depression and heterodyne interference effects in various individual circuits which form portions of a typical receiving system.

It is shown that the degree of signal depression in an f-m system differs from that in an a-m system primarily because of the limiting circuits employed in the usual f-m system. With FM, when effective limiting is provided together with a linear-slope filter, the signal depression effects become greater owing to the combination of limiter and discriminator circuits. The limiters used in f-m reception produce output distortion components which contain signal information. A wide-band discriminator circuit is necessary to retain as much of this information as possible. It is stressed that the annoying nature of the heterodyne in a narrow-band f-m system is a substantial detriment when compared to the heterodyne response in an a-m system.

PROBLEM STATUS

This report, together with NRL report R-3422, completes the investigation authorized under Problem S1364A.

AUTHORIZATION

NRL Problem R01-19R (BuShips Request S1364)

INVESTIGATION OF NONLINEAR RECEIVING CIRCUITS UNDER TWO-SIGNAL CONDITIONS

INTRODUCTION

The studies here reported were concerned with segregation of signal depression effects in various individual circuits which formed portions of a typical receiving system, and with experimental determination of the magnitude of the associated phenomena. This material supplements the treatment presented in NRL Report R-3422. (1)* Additionally, the interaction of common-channel signals to produce the form of interference generally known as a heterodyne is considered in detail herein, so that this report, together with R-3422, constitutes a study of a-m and f-m systems under common-channel operational conditions.

THE EFFECTS OF LIMITING

Experimental Circuits Employed

Experimental information concerning the signal depression effect due to the limiter alone, as well as data concerning the output frequencies obtained from a limiter were essential to the completion of the investigation covered in these reports. In order to facilitate measurements and eliminate variables, it was decided to conduct the limiter study at audio frequencies. A good limiter, approaching the best obtainable, was required. The limiter-amplifier contained in the Model X-FRG frequency-shift converter equipment appeared excellent for this purpose. A complete description of the equipment and its characteristics is included in a previous Laboratory report. (6) Briefly, the Model X-FRG converter has several cascaded limiters arranged as follows. The initial stage consists of a 6SL7GT(V-101) twin-triode, operated as a cathode-coupled limiter-amplifier. The second stage consists of a 6J5 triode used as a linear amplifier with a gain of approximately 18 db. A cascaded second limiter-amplifier employs another 6SL7GT(V-103), connected similarly to V-101. Both of these stages are designed to provide a limited output level of approximately 5.0 volts. The limiters do not draw grid current; hence there is no change in coupling condenser charge caused by such current. Since the limiter-amplifier is untuned, there are no tuned circuits to restore the sinusoidal waveform at the output. The arrangement used provided an excellent example of cascaded saturation-type limiting.

A circuit diagram of this limiter-amplifier as actually employed is shown in Figure 1. A few modifications were made in the circuit to facilitate measurements. The input connections were modified so as to by-pass the frequency selective circuits, making the limiter

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* *References are listed at the end of the report.*

relatively broad-band in response. The two separate input signal sources were connected in series between the signal grid of V-101, the first limiter-amplifier, and ground. A 6SJ7 amplifier (V-104), was converted into a decoupling cathode follower. The input-output characteristics of this cathode-follower were known, and they were linear within the range employed during the measurements. The insertion loss was 2.7 db. The frequency response of the cathode-follower was flat within one decibel from 50 to 16,000 cps.

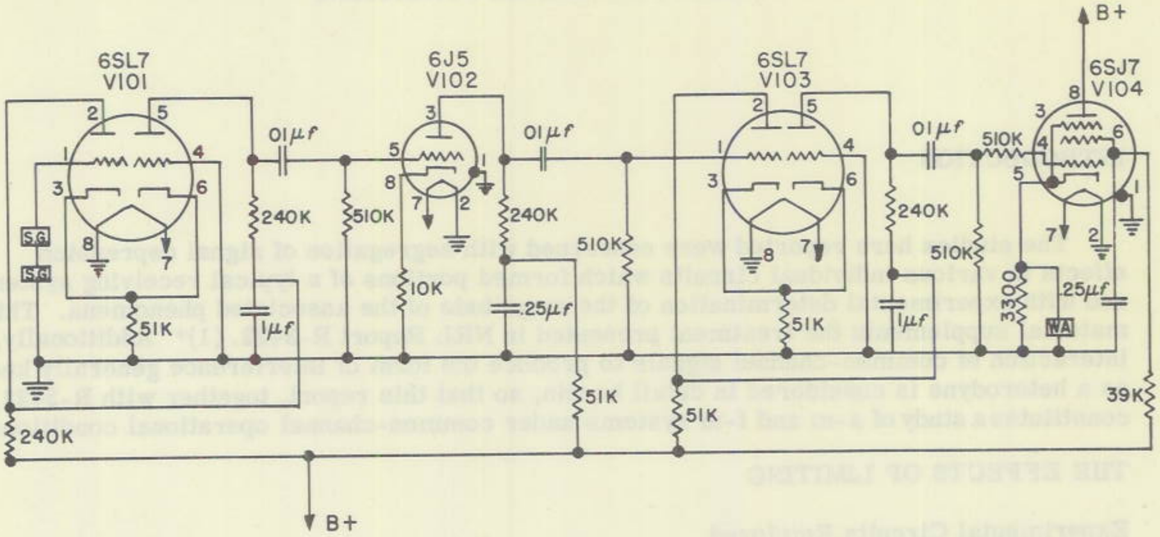

Figure 1 - Cascaded limiter-amplifier system

Output from the limiter-amplifier was measured across the 3300-ohm cathode resistor in this cathode-follower stage. A Hewlett-Packard, Model 300-A, Selective Wave Analyzer was used at all times for output measurements. For frequency measurements, a General Radio, Type 617C, Interpolation Oscillator was employed. The wave analyzer was always employed in its most selective condition.

Before two-signal measurements were made, certain of the one-signal characteristics of the entire limiter-amplifier were checked. The frequency response obtained is shown in Figure 2. The curve is flat within one decibel from 100 to 7500 cps, and is within 6 decibels of optimum response from 30 to 20,000 cps. This was satisfactory for these tests, and no corrections have been made in the data (to be presented later in this report) for differences due to a frequency response which was so nearly uniform over the range of interest.

Measurements of output voltage as a function of applied 2000 cps input are shown in Figure 3. The amplifier is linear until an input level of approximately 20 millivolts is reached. The output is essentially constant for input levels greater than 50 millivolts, up to 200 volts, which was the maximum input voltage applied. This curve, Figure 3, represents a good limiter characteristic. The output potential shown was measured with a Ballantine Electronic Voltmeter; hence it includes the rms of all harmonic output components as well as the fundamental.

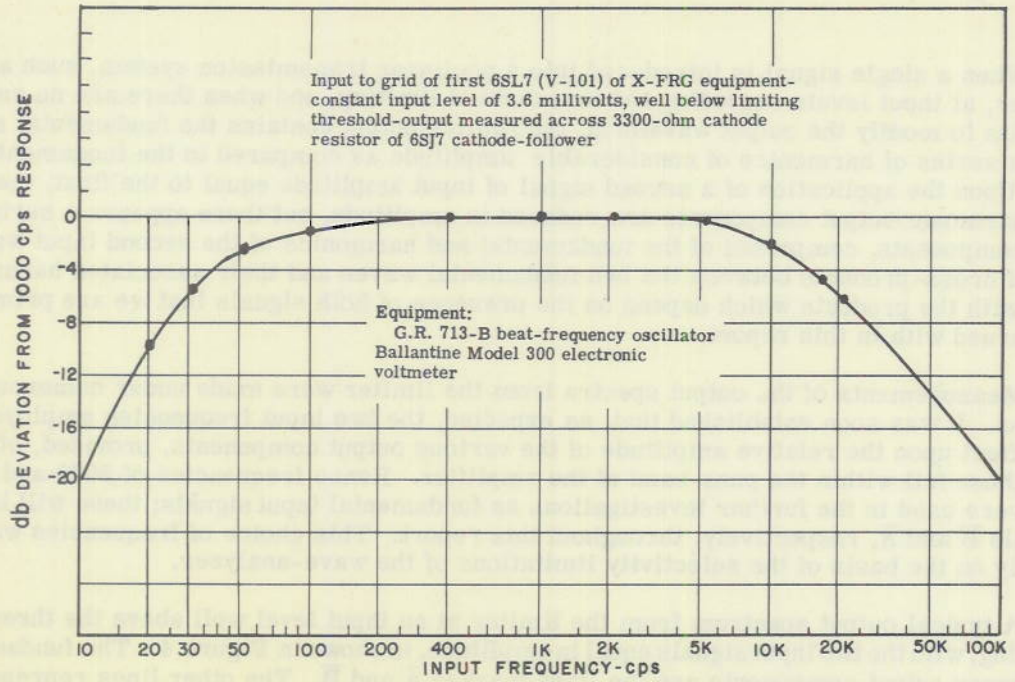

Figure 2 - Limiter-amplifier frequency response

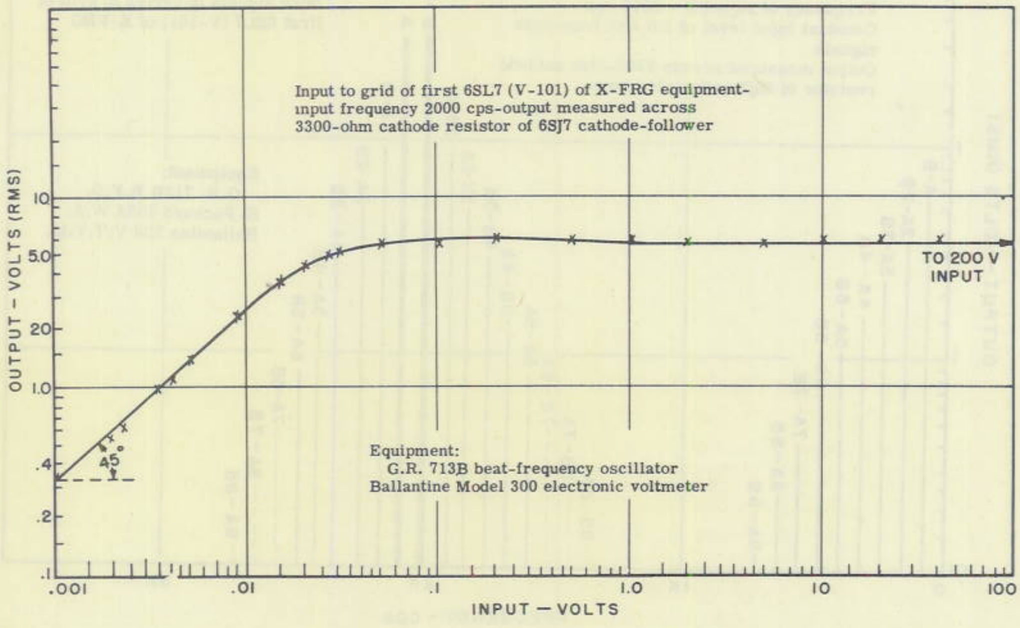

Figure 3 - Limiter-amplifier output characteristics

Output Spectrum of Limiter

When a single signal is introduced into a nonlinear transmission system, such as a limiter, at input levels exceeding the threshold of limiting, and when there are no selective circuits to modify the output waveform, the limiter output contains the fundamental signal plus a series of harmonics of considerable amplitude as compared to the fundamental output. Upon the application of a second signal of input amplitude equal to the first, the original harmonic output components are reduced in amplitude, but there appears a series of new components, comprised of the fundamental and harmonics of the second input wave, and of cross-products between the two fundamental waves and their associated harmonics. It is with the products which depend on the presence of both signals that we are primarily concerned with in this report.

Measurements of the output spectra from the limiter were made under numerous conditions. It was soon established that, as expected, the two input frequencies employed had no effect upon the relative amplitude of the various output components, provided, of course, that these fell within the pass-band of the amplifier. Hence frequencies of 2000 and 2080 cps were used in the further investigations as fundamental input signals; these will be called signals $\overline{B}$ and $\overline{A}$, respectively, throughout this report. This choice of frequencies was made mainly on the basis of the selectivity limitations of the wave-analyzer.

A typical output spectrum from the limiter at an input level well above the threshold of limiting, with the two input signals equal in amplitude, is shown in Figure 4. The fundamental-frequency output components are the lines marked $\overline{A}$ and $\overline{B}$. The other lines represent all the significant members of the series of cross-products having amplitude values of over 1 percent of the fundamental, and lying within the frequency region of interest in this study.

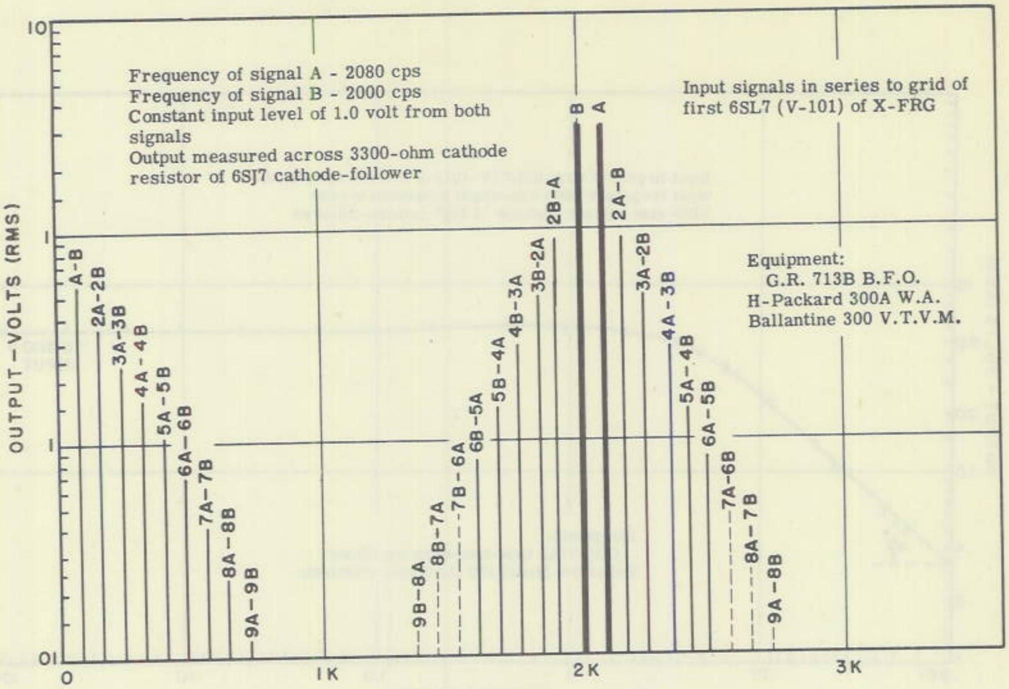

Figure 4 - Output spectrum from limiter

Similar series are found around all the harmonics of $\overline{A}$ and $\overline{B}$ (around 4000, 6000, 8000 cps, etc.), but these are not included in Figure 4. As expected, when the two input signals are equal, the fundamental output components are equal, as are their harmonics. Likewise, the components appearing on either side of $\overline{A}$ and $\overline{B}$ in frequency are equal in amplitude, i.e., $\overline{2B - A} = \overline{2A - B}$, $\overline{3B - 2A} = \overline{3A - 2B}$, etc. In the same manner, the $\overline{A\text{-}B}$ and $\overline{A\text{+}B}$ outputs are equal. This pattern, of course, will be modified by any selective circuits beyond the limiter; but assuming the frequency difference between carriers to be extremely small in comparison to the bandwidth of subsequent circuits, this will be the pattern at the limiter output terminals within the particular pass-band of interest.

Attention is directed to the components $\overline{2A - B}$ and $\overline{2B - A}$. It should be noted that these are cross-products of the lowest order possible in the band around $\overline{A}$ and $\overline{B}$ and that they exceed in amplitude any of the other output components (aside from the fundamentals) in that band. Edwin Armstrong (7) discusses similar data which he obtained experimentally using a 400 kc limiter. When two signals, a strong one at 400 kc and a weaker one at 390 kc, were introduced into this limiter, an "image" (the words are Armstrong's) was observed at 410 kc. The significance of these components in the mechanics of f-m capture is fully discussed elswehere (1,2); in this report the discussion will be limited to the variation in the amplitude of these intermodulation components under various conditions of two-signal input.

The characteristic shown in Figure 4 is typical of those obtained with input signals well above the threshold of limiting. A plot showing how four of the principal intermodulation output frequencies vary with input signal amplitude is presented in Figure 5. The two input signals were varied in absolute amplitude, but were always maintained equal to each other. As indicated, the spectrum is identical at all input levels beyond 100 millivolts, where the limiter is essentially constant in its one-signal response (see Figure 3). As the input levels are reduced to the neighborhood of the limiter threshold, the immediate $\overline{A}$ and $\overline{B}$ side-responses ($\overline{2B - A}$, $\overline{2A - B}$, $\overline{3B - 2A}$, etc.) begin to fall off sooner than do the $\overline{A\text{-}B}$ and $\overline{A\text{+}B}$ responses and the $\overline{A\text{-}B}$ and $\overline{A\text{+}B}$ responses exceed the $\overline{2B - A}$ and $\overline{2A - B}$ responses whenever the input levels drop below the limiter threshold.

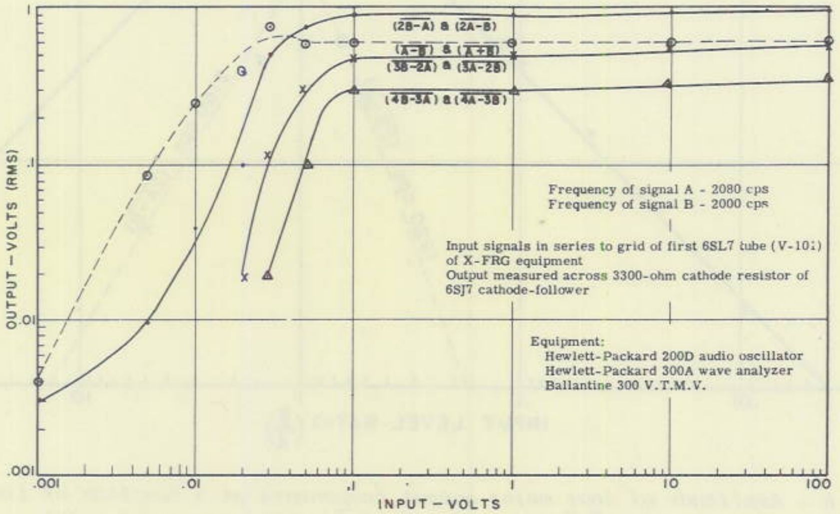

Figure 5 - Amplitude of four major intermodulation output components as a function of limiter input level (input amplitude of $\overline{A}$ = input amplitude of $\overline{B}$ at all input levels)

The variation of the amplitudes of the $\overline{2B-A}$ and $\overline{2A-B}$ responses when the input amplitude ratio of the fundamental signals, $\overline{A}$ and $\overline{B}$, is varied will next be considered. A typical curve demonstrating the variation is presented in Figure 6. This information was obtained with a constant $\overline{A}$ signal input level of 1.0 volt, a value which provided full limiting. The solid curves represent the output values of the fundamental frequency components and the dotted curves show the output values of the $\overline{2B-A}$ and $\overline{2A-B}$ components. The input level of the $\overline{B}$ signal was varied as indicated by the input ratio $\overline{B}/\overline{A}$.

When the two signals are equal, the output amplitudes of $\overline{2A-B}$ and $\overline{2B-A}$ are equal, just as are $\overline{A}$ and $\overline{B}$. The output level of $\overline{2B-A}$ is maximum when the input level of $\overline{B}$ exceeds that of $\overline{A}$ by approximately 3 db, and the output $\overline{2A-B}$ is maximum when the input level of $\overline{A}$ exceeds that of $\overline{B}$ by approximately 3 db. The measurements (and listening tests) thus have indicated that whenever the signal input differential exceeds about 3 db, the output amplitudes of the weaker fundamental and its corresponding "image" are equal and remain equal until they completely disappear (complete capture). The slopes of the curves show this proportionality, i.e., the slope of $\overline{2A-B}$ when $\overline{A}$ is the stronger signal by more than 3 db is 45 degrees, and the slope of $\overline{2B-A}$ when $\overline{B}$ is stronger by more than 3 db is also 45 degrees. This confirms the experimental results of Armstrong. (Reference 7, Figure 12, p. 706.) It should be noted, however, that on the other side of input equality the slope of the intermodulation components, $\overline{2A-B}$ and $\overline{2B-A}$, is greater (about 60 - 70°).

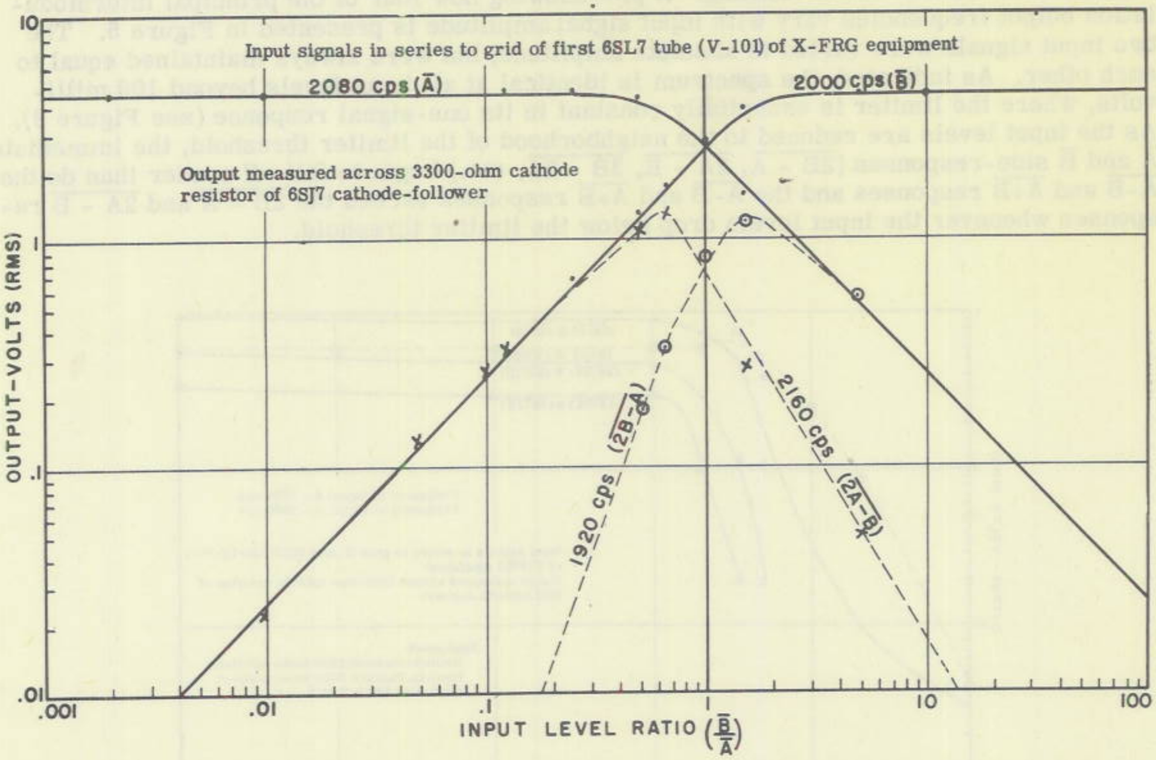

Figure 6 - Amplitude of four major output components as a function of limiter input level ratio $\overline{B}/\overline{A}$ (input level of $\overline{A}$ held constant at 1 volt)

There has previously been thorough treatment in technical literature of the relative output of the two fundamental components ($\overline{A}$ and $\overline{B}$) from a perfect limiter. Wheeler has obtained an expression for the output values of both fundamental signals by trigonometric transformations, followed by an evaluation of their average amplitude by integration (8). Final evaluation of the output levels requires evaluation of elliptic integrals. Wheeler's calculations show that the output component amplitude of both fundamental signals should be reduced by a factor $2/\pi$, or approximately 4 db, when their input levels are equal. When there is a sizeable difference between the two input signal levels, the weaker signal is reduced to an amplitude 1/2 (W/S) where W is the weaker signal input, and S is the stronger signal input value. This produces the 45 degree slope shown in Figure 6; a similar curve is shown in Wheeler's work. (Reference 8, Figure 7, page 12.) It should be noted that the characteristic shown in Figure 6 is in agreement with that theoretically obtained above in a perfect limiter, insofar as the fundamental output components ($\overline{A}$ or $\overline{B}$) are concerned. The stronger signal is held to a uniform output value whenever the input signal differential is greater than about 6 db. The weaker signal is reduced almost precisely as the ratio $(\overline{W}/S)$-6db, leading to the predicted slope of 45 degrees. It must be stressed that these capture curves (Figure 6) indicate the depressions of carrier output level as measured at audio frequencies, and do not represent the depression of carrier modulation. The main capture report discusses the effects of signal modulation and what happens to the capture slope when the spectral components of Figure 4 are transmitted through an amplitude and frequency sensitive device such as an f-m detector. Only the components appearing in the limiter output are discussed here, with no consideration given (as yet) to subsequent f-m detection. In brief, so far as the fundamental output component of the weaker carrier from the limiter is concerned, the depression or capture slope of that carrier's output component is the same regardless of the modulation originally appearing on either carrier at the input to the limiter; i.e., capture is an amplitude effect which is dependent solely on the absolute and relative amplitudes of the desired and interfering carriers within the frequency pass-band of the receiver.

A number of similar two-signal characteristics were obtained at different input levels to the limiter-amplifier. All such characteristics from 0.05 to 100 volts were virtually identical. Two other characteristics are included in this report to show the effects of below-threshold limiter operation. The first (Figure 7) is that obtained with a fixed $\overline{A}$ input signal of 0.02 volts. This level is close to the limiter threshold value. The slopes of the fundamental ($\overline{A}$ and $\overline{B}$) output components are seen to be 45 degrees, similar to the slopes of the above-threshold limiting case shown in Figure 6. The output components $\overline{2A - B}$ and $\overline{2B - A}$, however, show somewhat different characteristics at this level, as is to be expected from the data presented in Figure 5.

In Figure 8, a capture characteristic is shown for the condition of the $\overline{A}$ signal held constant at a value below the limiting level (0.005 volt). Only the $\overline{A}$ and $\overline{B}$ output signals appear in this graph, since the components at other frequencies were not of sufficient amplitude to be shown. There is almost no capture of signal $\overline{A}$ up to an input level of 0.02 volt (input ratio $\overline{B}/\overline{A} = 4$), which is the threshold of limiting. The slight depression of $\overline{A}$ signal output for $\overline{B}$ signal input levels ranging from below 0.001 to about 0.02 volt is probably a measure of existing nonlinearity in the amplifier transmission characteristic. The break in the output characteristic of $\overline{A}$ at the limiting threshold is abrupt. From an almost-horizontal line, it suddenly assumes a 45-degree downward slope in the limiting region.

In order to check the effects of the addition of further limiting to an already effective limiter, a full-wave shunt-limiter employing two Western Electric D171561 crystal

rectifiers was inserted between the X-FRG output and the measuring equipment. A circuit diagram of this shunt-limiter circuit is shown in Figure 9. The added limiter stage was similar to that employed in system capture measurements with the Model X-RDZ-2 receiver (1). Its insertion loss, below limiting levels, was 1 db. The over-all threshold of limiting with the added limiter was found to be about half that for the X-FRG limiter-amplifier alone, or approximately 10 millivolts; and the limited output level was about 1.5 volts, as compared to approximately 4.5 volts from the X-FRG alone. The characteristic shown in Figure 10 was obtained with the $\overline{A}$ signal maintained constant at 1.0 volt input level. It is thus directly comparable to that shown in Figure 6. Comparison of the two figures shows that the curves are virtually identical insofar as the capture slopes are concerned. These slopes for both the output fundamental signals and their respective side responses are very close to 45 degrees. The slopes of $\overline{2B - A}$ when $\overline{A}$ is stronger than $\overline{B}$, and $\overline{2A - B}$ when $\overline{B}$ is stronger than $\overline{A}$, are between 60 and 65 degrees. The maximum fundamental signal output level is lower, owing to the additional limiting, but the relative amplitudes and the slopes of the respective curves of Figures 6 and 10 are very similar to each other.

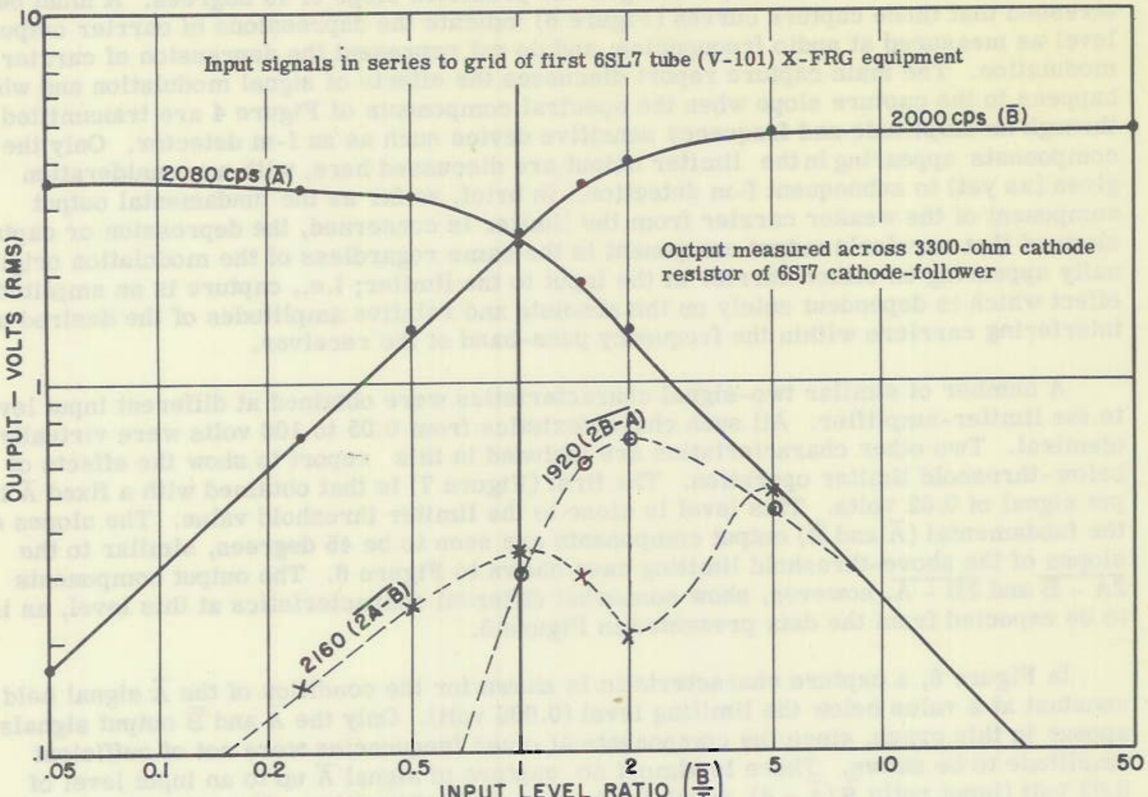

Figure 7 - Amplitude of four major output components as a function of limiter input level ratio $\overline{B}/\overline{A}$ (input level of $\overline{A}$ held constant at 0.02 volt (limiter threshold))

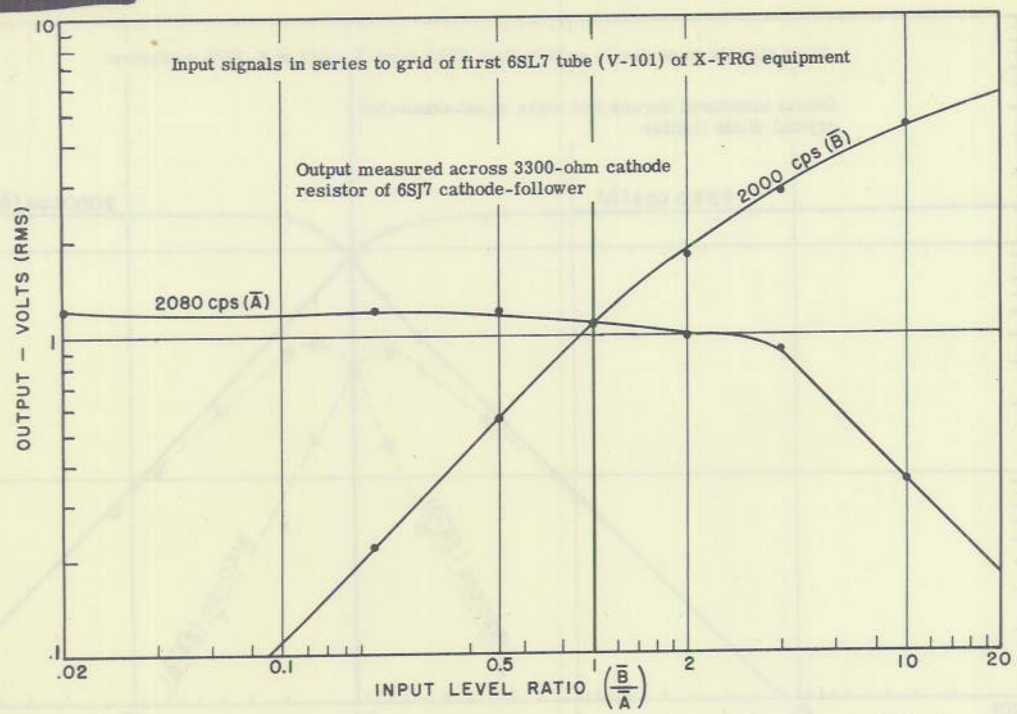

Figure 8 - Amplitude of two major output components as a function of limiter input level ratio $\overline{B}/\overline{A}$ (input level of $\overline{A}$ held constant at 0.005 volt (below limiter threshold))

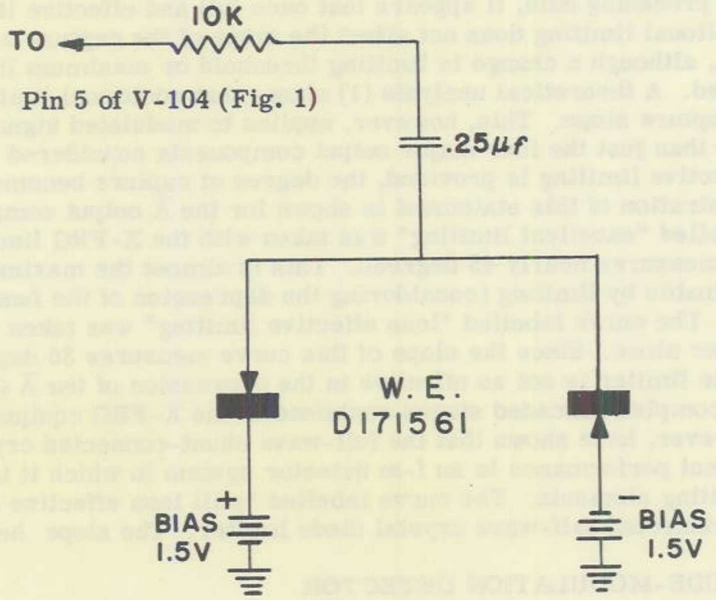

Figure 9 - Full-wave shunt-limiter circuit employing crystal diodes

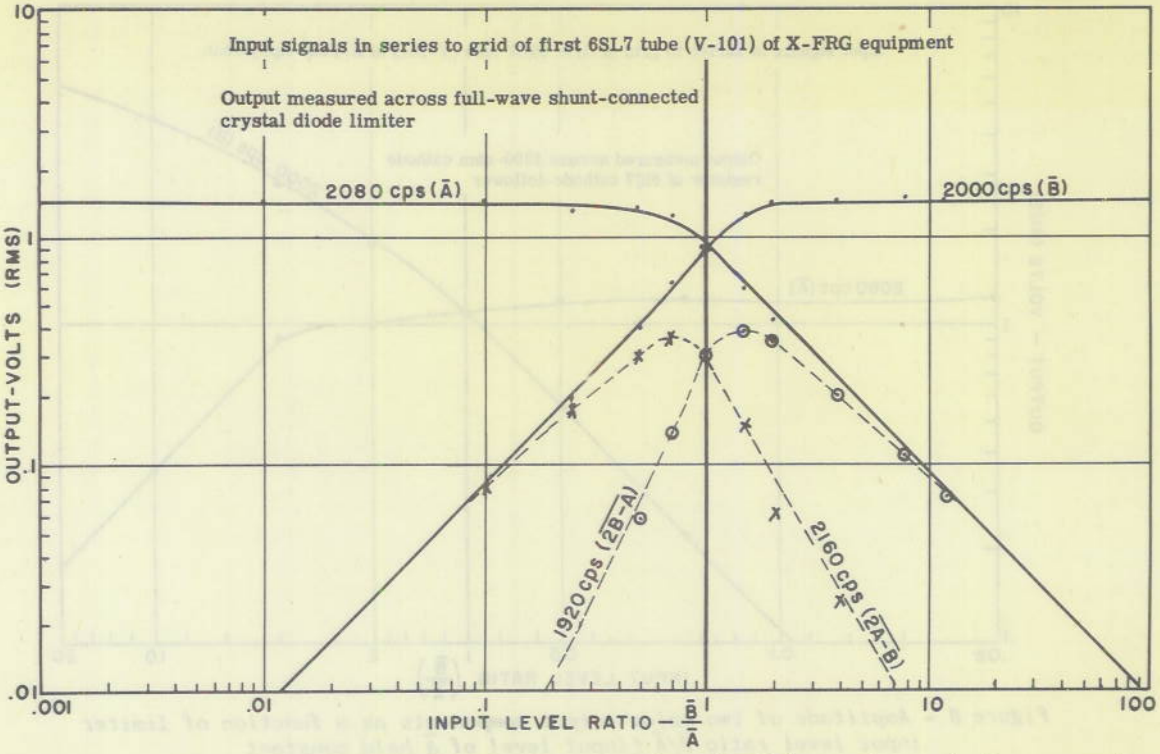

Figure 10 - Effect of added limiter stages on amplitude of four major output components as a function of limiter input level ratio $\bar{B}/\bar{A}$ (input level of $\bar{A}$ held constant at 1 volt)

From the preceding data, it appears that once full and effective limiting has been achieved, additional limiting does not affect the slope of the capture curve for the components shown, although a change in limiting threshold or maximum limited output level may be obtained. A theoretical analysis (1) shows that additional limiting should increase the over-all capture slope. This, however, applies to modulated signals and includes the effect of more than just the four major output components considered in Figures 5 to 10. When less effective limiting is provided, the degree of capture becomes less. Experimental demonstration of this statement is shown for the $\bar{A}$ output component in Figure 11. The curve labelled "excellent limiting" was taken with the X-FRG limiter-amplifier system, and the slope measures nearly 45 degrees. This is almost the maximum capture slope normally obtainable by limiting (considering the depression of the fundamental output components only). The curve labelled "less effective limiting" was taken with a full-wave crystal diode limiter alone. Since the slope of this curve measures 36 degrees, it would appear that this simple limiter is not as effective in the depression of the $\bar{A}$ output component as are the more complex cascaded stages contained in the X-FRG equipment. Other measurements, (1) however, have shown that the full-wave shunt-connected crystal diode limiter will provide excellent performance in an f-m detector system in which it is used in combination with other limiting elements. The curve labelled "still less effective limiting" was taken with a shunt-connected half-wave crystal diode limiter. The slope here is about 20 degrees.

THE AMPLITUDE-MODULATION DETECTOR

Experimental Circuits Employed

In the investigation of the performance of both a conventional a-m and a conventional f-m demodulator, the detector circuits in the Navy Model RBK-1 receiver were used. Both a-m and f-m demodulator circuits were already provided in this equipment without need for modification or re-design. Also, since the center frequency of the i-f amplifier system in the equipment was 5.25 Mc, f-m signal generators were available without necessity of modification. The f-m detector circuit used (Figure 12) was of the conventional Foster-Seeley type, and therefore did not possess any inherent low-level limiting. Thus the detector investigation would not be complicated by undesired limiting effects. The fairly low i-f amplifier center-frequency facilitated the accuracy of measurements as well as simplifying test equipment problems.

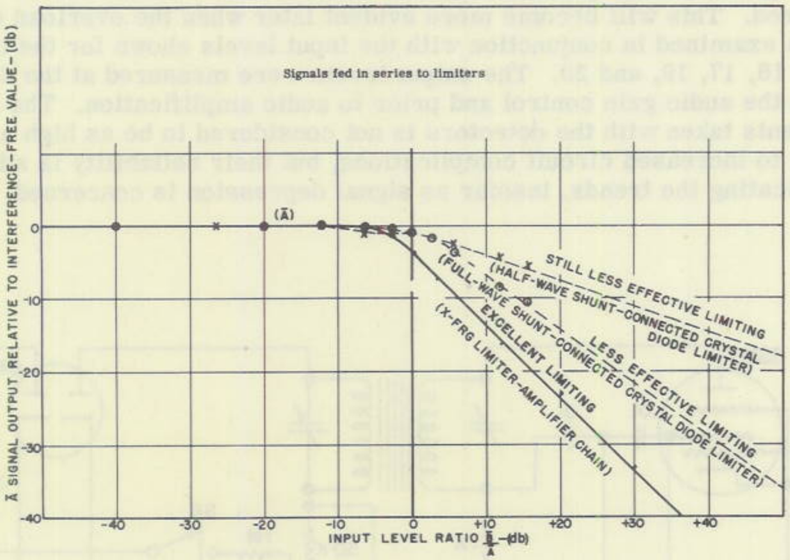

Figure 11 - Effect of various degrees of limiting on $\bar{A}$ signal output component ($\bar{A}$ signal input held constant at 2.0 volts)

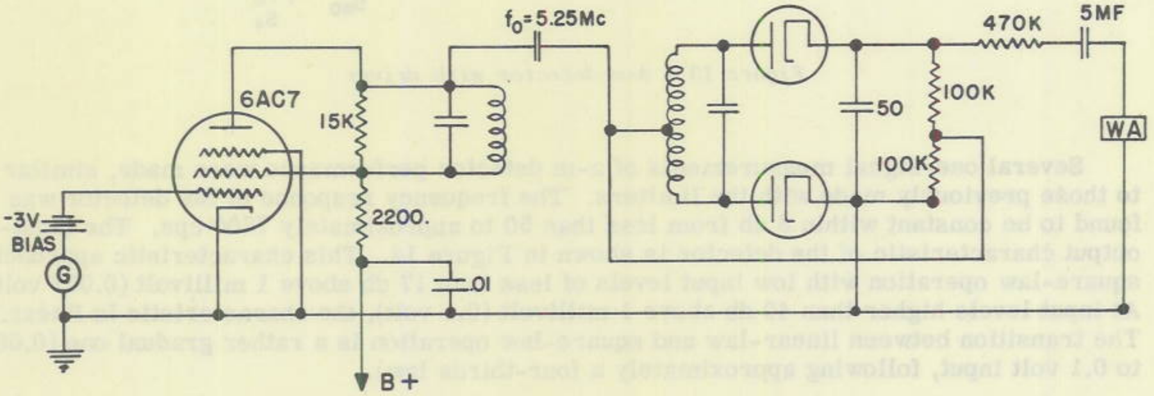

Figure 12 - Balanced f-m detector with driver

A complete description and schematic diagram of the Model RBK-1 receiver may be found in its instruction book. The signals were introduced at the grid of the tube preceding the demodulator, for two reasons. First, this provided isolation of the signal-generators from the detector transformers, which was most desirable, particularly in FM. Also, the amplification of the stage preceding the detector permitted the application of high level signals (over 10 volts rms) to the detector stage. In the case of the a-m receiver, this buffer stage consisted of a 6SK7 pentode amplifier, followed by a conventional 6H6 diode detector (see Figure 13). Consideration was given to saturation effects in the 6SK7 buffer stage, but investigation indicated that no serious errors due to such effects were encountered. This will become more evident later when the overload characteristic of Figure 14 is examined in conjunction with the input levels shown for the capture curves of Figures 15, 16, 17, 19, and 20. The output levels were measured at the detector output load preceding the audio gain control and prior to audio amplification. The accuracy of the measurements taken with the detectors is not considered to be as high as that for the limiters owing to increased circuit complications, but their reliability is adequate for the purpose of indicating the trends, insofar as signal depression is concerned.

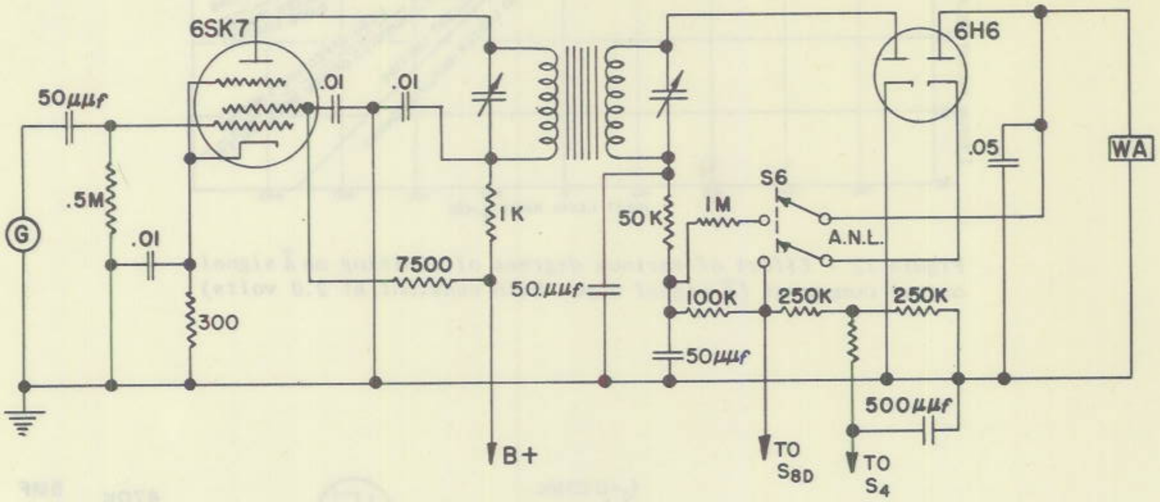

Figure 13 - A-m detector with driver

Several one-signal measurements of a-m detector performance were made, similar to those previously made with the limiters. The frequency response of the detector was found to be constant within 6 db from less than 50 to approximately 7500 cps. The input-output characteristic of the detector is shown in Figure 14. This characteristic approaches square-law operation with low input levels of less than 17 db above 1 millivolt (0.007 volt). At input levels higher than 40 db above 1 millivolt (0.1 volt), the characteristic is linear. The transition between linear-law and square-law operation is a rather gradual one (0.007 to 0.1 volt input, following approximately a four-thirds law).

For two-signal measurements, two modulated carriers were used at all times. The percentage modulation of the two signals was varied, but, to avoid unnecessary complication, the modulation percentage of each signal was always made equal to that of the other. To facilitate spectrum measurements, the two carriers were modulated at 2000 and 2080 cps

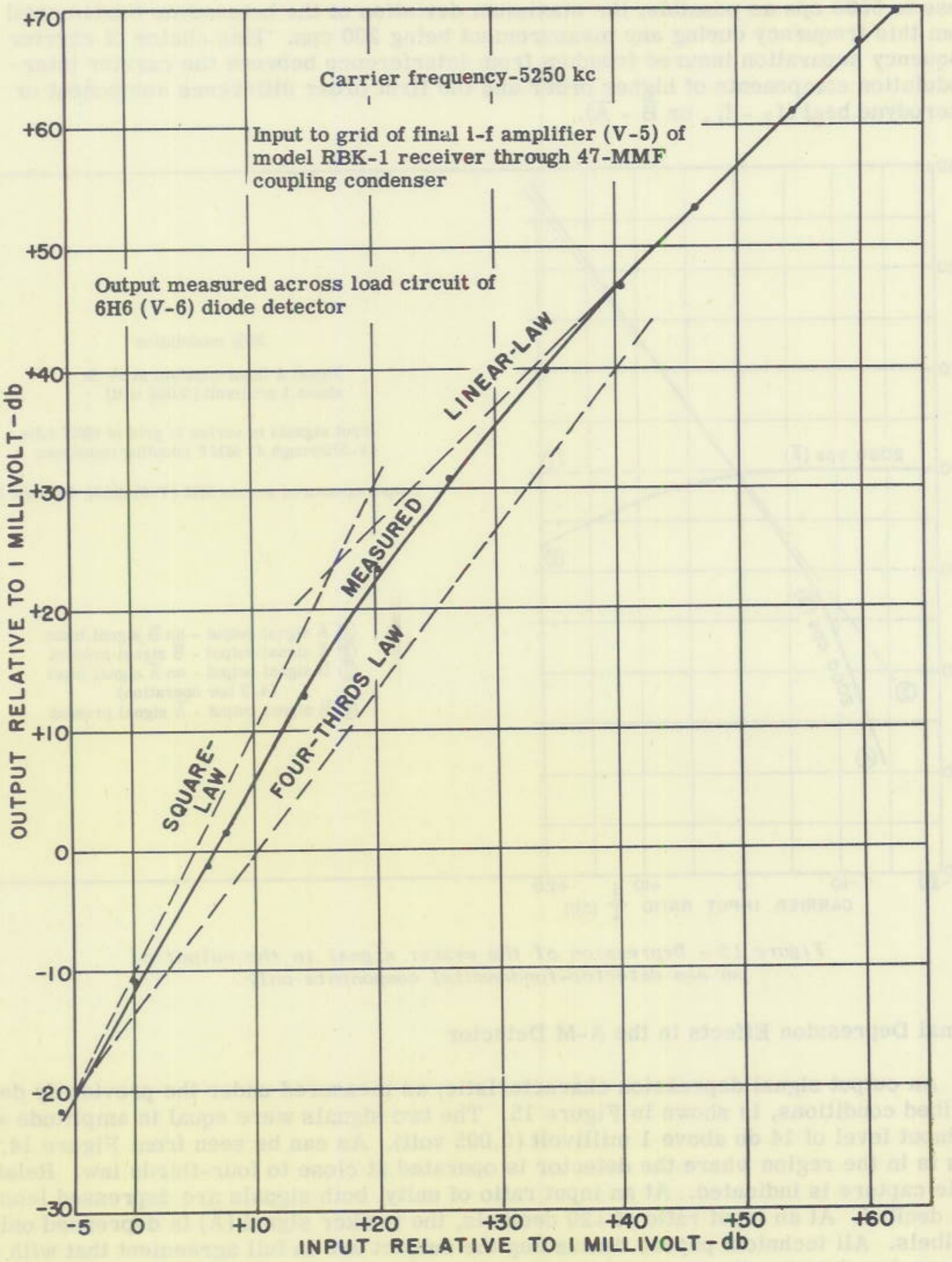

Figure 14 - A-m detector transmission characteristic (input carrier modulated 30% at 2080 cps)

[redacted]

respectively. The frequency separation between the two carriers was maintained as close to 3500 cps as possible, the maximum deviation of the heterodyne fundamental from this frequency during any measurement being 200 cps. This choice of carrier frequency separation insured freedom from interference between the carrier intermodulation components of higher order and the first order difference component or heterodyne beat ($f_2 - f_1$, or $\overline{B} - \overline{A}$).

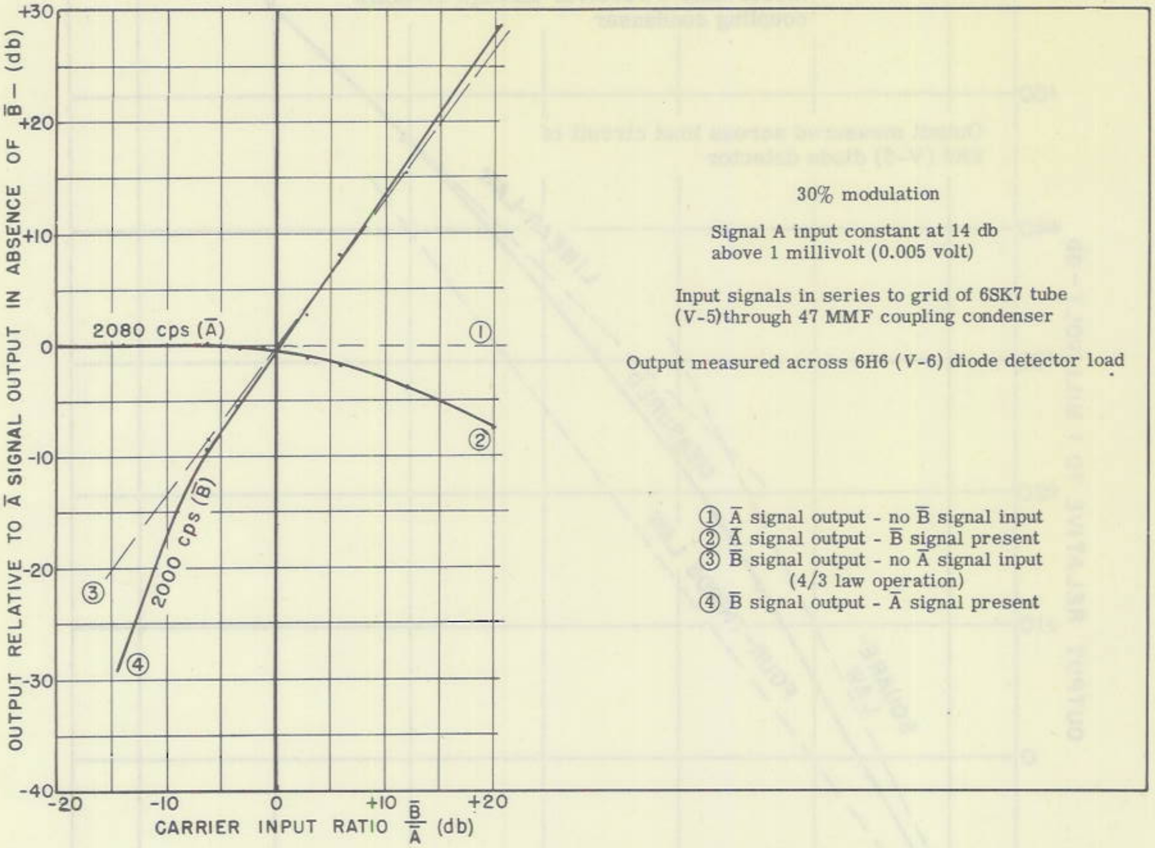

Figure 15 - Depression of the weaker signal in the output of an a-m detector—fundamental components only

Signal Depression Effects in the A-M Detector

An output signal depression characteristic, as measured under the previously described conditions, is shown in Figure 15. The two signals were equal in amplitude at an input level of 14 db above 1 millivolt (0.005 volt). As can be seen from Figure 14, this is in the region where the detector is operated at close to four-thirds law. Relatively little capture is indicated. At an input ratio of unity, both signals are depressed less than one decibel. At an input ratio of +20 decibels, the weaker signal ($\overline{A}$) is depressed only 7 decibels. All technical papers discussing the subject are in full agreement that with a square-law detector there should be no capture effect (9, 10, 11, 12). This has also been shown in Appendix B of the main capture report (1). The capture observed in Figure 15 may properly be attributed to the departure of the detector from perfect square-law operation at the input levels used in this measurement.

[redacted]

The output characteristics next to be considered were obtained at higher detector input levels, signal input equality in this case being at 34 db above 1 millivolt (0.05 volt). As indicated in Figure 14, this level is the lowest at which reasonably linear operation was obtained. In Figure 16, the characteristic for 30 percent modulation is shown, and in Figure 17 the characteristic for 80 percent modulation is shown. As indicated, the curves are virtually independent of the percentage of modulation applied to the two carriers, despite the opinion expressed in one paper (13). It should be noted that the fundamental output component of $\bar{A}$, the signal with constant input level, is in both cases depressed between 3 and 4 decibels when the signals are equal. When $\bar{A}$ is the weaker input signal, the curve assumes a 45-degree slope, similar to that of the fundamental output component of the weaker carrier obtained with a good limiter. It would thus seem that depression of the fundamental modulation output component in a linear-law detector is similar to that previously described for the weaker carrier in an effective limiter.

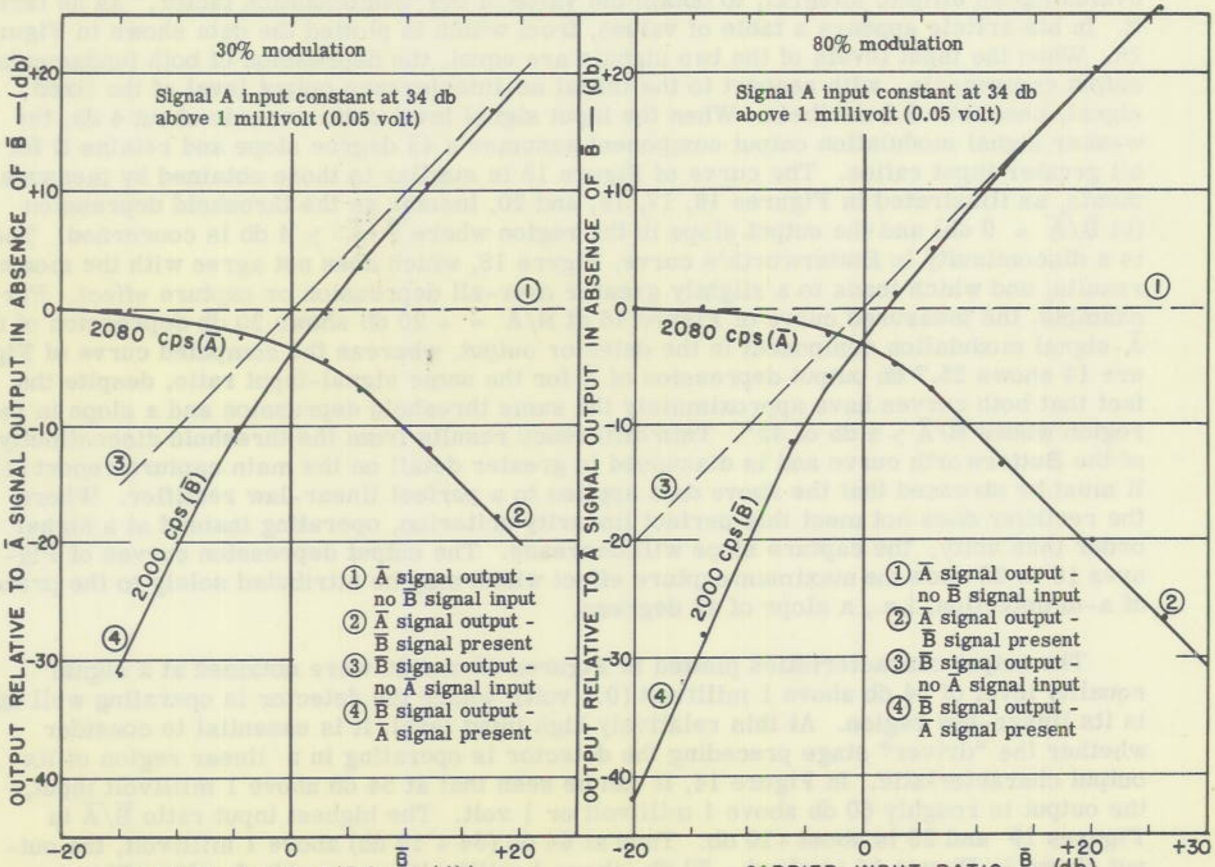

Figure 16 *Figure 17*

Depression of the weaker signal in the output of an a-m detector—fundamental components only

Several authors have written excellent papers on the output modulation depression occurring in linear-law detectors (10, 11, 12, 14, 15). All of these articles are in essential agreement on the mechanism, as well as the degree of the depression or capture effect. Appleton and Bookariwalla (10) derived an expression for the degree of depression,

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which they stated applied wherever the signal input ratio exceeded unity by a substantial amount (> 2). The complete derivation can be found in Appendix A of the main capture report (1). In brief, they found that the weaker signal would be depressed according to the equation:

$$y = \frac{1}{2}\left(\frac{W}{S}\right)$$

where y is the ratio of the weaker signal output with the stronger signal present to that with the stronger signal absent, and W and S are the weaker and stronger signal-input amplitudes, respectively. This is seen to be identical with the limiter expression mentioned previously.

One of the earliest papers on this subject was by Butterworth (11). His work involved evaluating an elliptic integral, to obtain the value of the "demodulation factor," as he termed it. In his article appears a table of values, from which is plotted the data shown in Figure 18. When the input levels of the two signals are equal, the depression of both fundamental output components, with respect to the initial no-interference output level of the fixed signal, should be 3.8 decibels. When the input signal level ratio exceeds about 4 db, the weaker signal modulation output component assumes a 45 degree slope and retains it for all greater input ratios. The curve of Figure 18 is similar to those obtained by measurements, as illustrated in Figures 16, 17, 19, and 20, insofar as the threshold depression (at $\overline{B}/\overline{A} = 0$ db) and the output slope in the region where $\overline{B}/\overline{A} > 4$ db is concerned. There is a discontinuity in Butterworth's curve, Figure 18, which does not agree with the measured results, and which leads to a slightly greater over-all depression or capture effect. For example, the measured curve of Figure 16 at $\overline{B}/\overline{A} = +20$ db shows 20 db depression of the $\overline{A}$-signal modulation component in the detector output, whereas the computed curve of Figure 18 shows 25.7 db output depression of $\overline{A}$ for the same signal-input ratio, despite the fact that both curves have approximately the same threshold depression and a slope in the region where $\overline{B}/\overline{A} > 4$ db of 45°. This difference results from the threshold discontinuity of the Butterworth curve and is discussed in greater detail on the main capture report (1). It must be stressed that the above data applies to a perfect linear-law rectifier. Where the rectifier does not meet this perfect linearity criterion, operating instead at a higher order than unity, the capture slope will decrease. The output depression curves of Figures 16 to 20 show the maximum capture effect which may be attributed solely to the process of a-m detection, i.e., a slope of 45 degrees.

The output characteristics plotted in Figures 19 and 20 were obtained at a signal equality level of 54 db above 1 millivolt (0.5 volt), where the detector is operating well up in its linear-law region. At this relatively high input level, it is essential to consider whether the "driver" stage preceding the detector is operating in a linear region of its output characteristic. In Figure 14, it can be seen that at 54 db above 1 millivolt input, the output is roughly 60 db above 1 millivolt or 1 volt. The highest input ratio $\overline{B}/\overline{A}$ in Figures 19 and 20 is about +10 db. Thus at 64 db (54 + 10 db) above 1 millivolt, the output shown in Figure 14 is about + 70 db above 1 millivolt, or roughly 3 volts. This is close to the region in which the 6SK7 buffer-amplifier tube begins to saturate. In any event, the capture slopes of the curves of Figures 19 and 20 are still 45 degrees and represent the maximum depression obtained with a linear-law detector alone.

The Heterodyne Output from an A-M Detector

In Figures 19 and 20, the output of the heterodyne (or difference-frequency fundamental component) is plotted together with the fundamental modulation output of the two signals. The heterodyne amplitude is such as to make it of primary concern in any study of common-channel interference. In the 30-percent modulation case, shown in Figure 19, the heterodyne output is greater in amplitude than the desired modulation output from either carrier for input ratios of -12 to +12 db, a rather large range of input level variation. Thirty-percent modulation is the average level generally maintained in a voice transmission system which is full modulated on peaks.

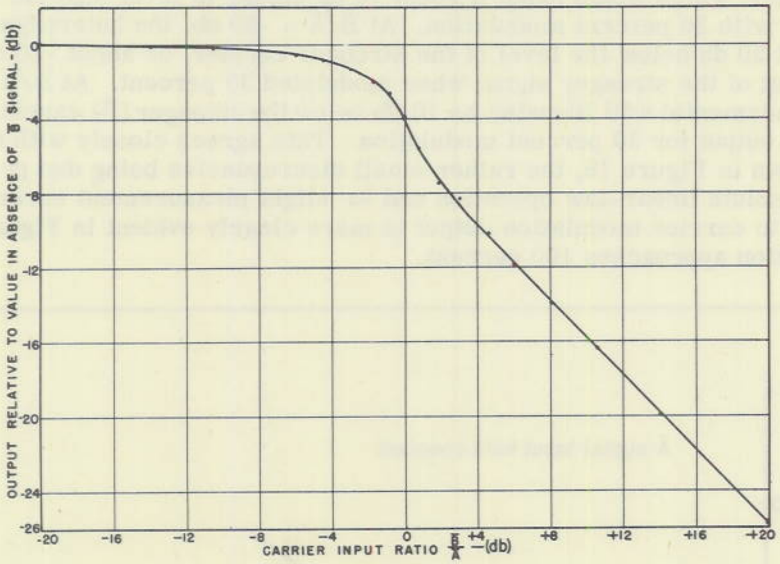


Figure 18 - Theoretical depression of weaker signal in output of a perfectly linear a-m demodulator

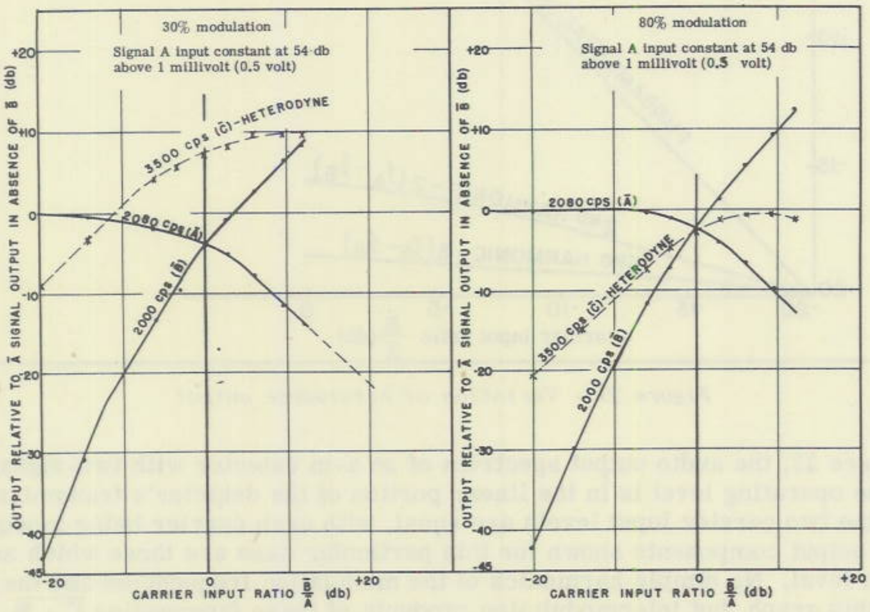


Figure 19 *Figure 20*

Depression of the weaker signal in the output of an a-m detector

The heterodyne fundamental output amplitude, as shown in Figures 19 and 20, is a function of both the relative and the absolute amplitudes of the two input carriers. The variation of the fundamental of the heterodyne envelope, as derived by Corrington (16), is shown in Figure 21. At $\overline{B}/\overline{A} = 1$ (0 db), this component is about 1.5 db below the level of either carrier, which would make it about 10 db higher in level than the audio output of either carrier with 30 percent modulation. At $\overline{B}/\overline{A} = -20$ db, the heterodyne fundamental would be about 20 db below the level of the stronger carrier, or about -10 db relative to the audio output of the stronger signal when modulated 30 percent. At $\overline{B}/\overline{A} = +10$ db, the heterodyne fundamental will likewise be 10 db below the stronger ($\overline{B}$) carrier or about equal to the $\overline{B}$ audio output for 30 percent modulation. This agrees closely with the relative output levels shown in Figure 19, the rather small discrepancies being due probably to departures from absolute linear-law operation and to slight measurement errors. The relation of heterodyne to carrier modulation output is more clearly evident in Figure 20, where the signal modulation approaches 100 percent.

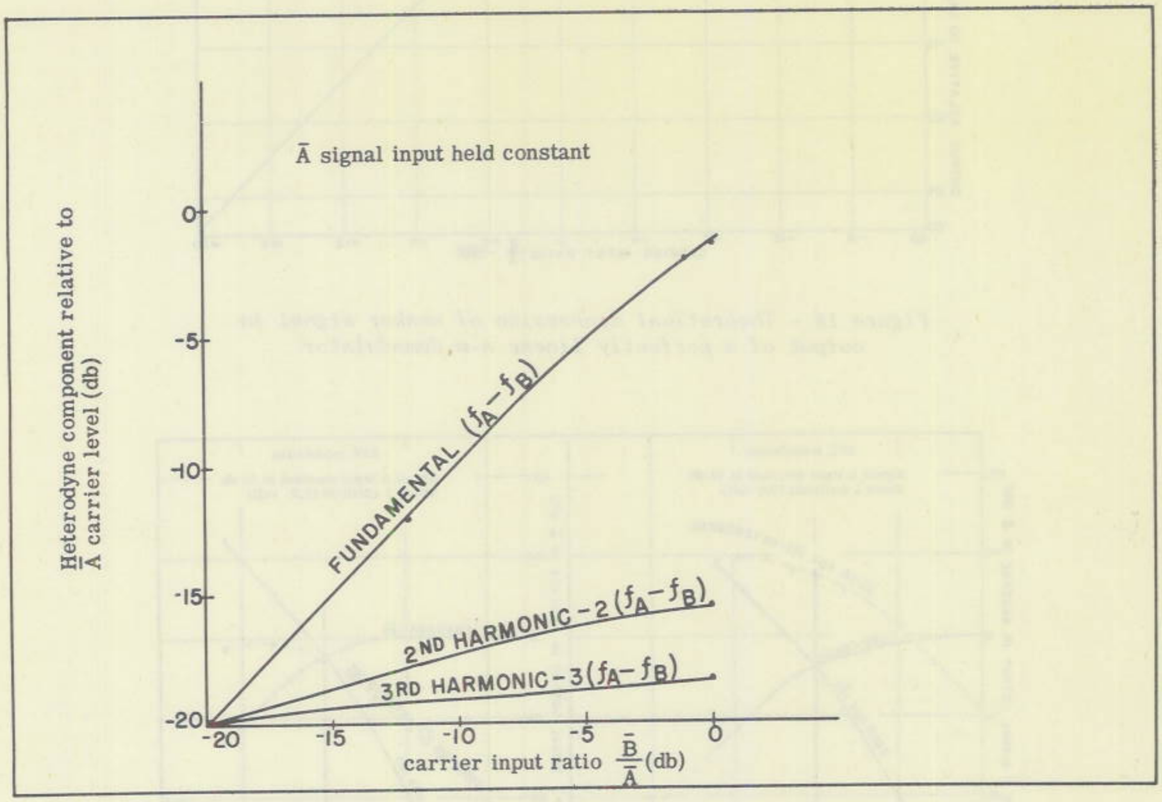


Figure 21 - Variation of heterodyne output

In Figure 22, the audio output spectrum of an a-m detector with two-signal input is shown. The operating level is in the linear portion of the detector's transmission characteristic, and the two carrier input levels are equal, with each carrier being modulated 30 percent. The output components shown for this particular case are those which are over 1 millivolt in level. No simple harmonics of the modulation frequencies and the heterodyne appear in this graph, but intermodulation products of these frequencies $\overline{C + B}$, $\overline{C + A}$, $\overline{C - (A - B)}$, and $\overline{C + (A - B)}$ are present. Modulation frequency difference components $\overline{2B - A}$ and $\overline{2A -}$ [illegible] are also present, but with much lower amplitude than products involving the heterodyne component. This is to be expected, since the heterodyne component, $\overline{C}$, is 12 db higher in value than the output components, $\overline{A}$ and $\overline{B}$, which have the original modulation frequencies and are next highest in output level. It is evident that the presence of the heterodyne tone at an audible frequency results in serious masking of the modulation components of the two signals. Similar masking effects by audible heterodyne will occur with square-law detection for equal signal input.

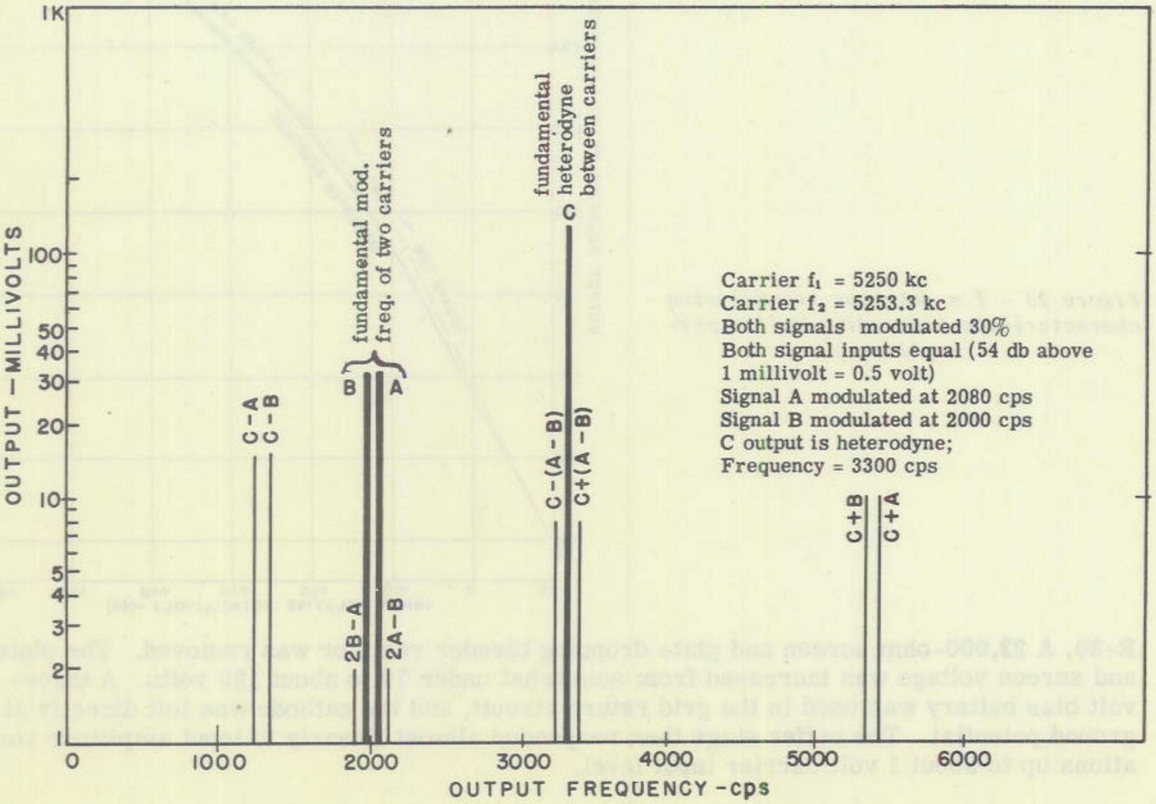


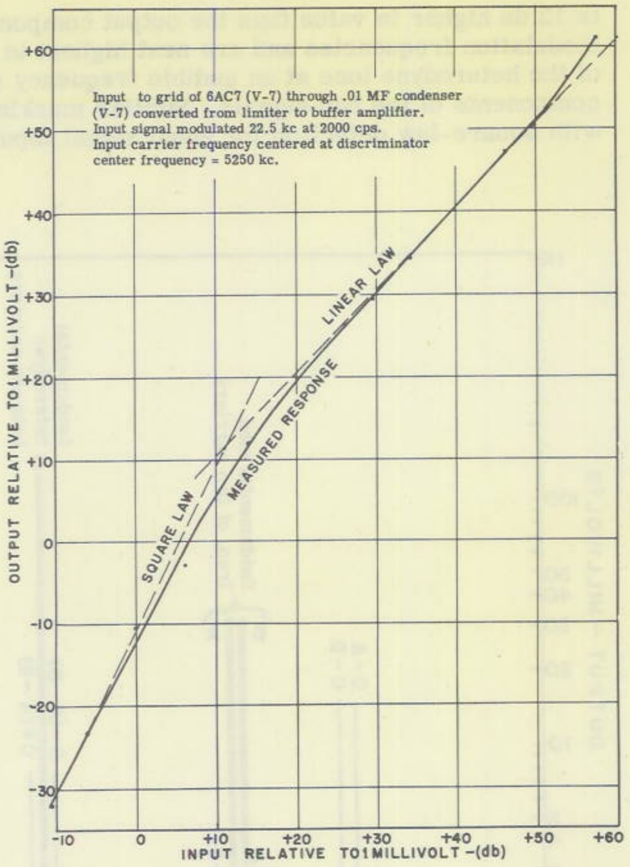
Figure 22 - Output spectrum of linear-law a-m detector with two-signal input

THE FREQUENCY-MODULATION DETECTOR

Experimental Circuits Employed

The reasons for use of the detector circuits of the Model RBK-1 receiver have been previously given in discussion of a-m detector performance. The circuit used for the f-m detector and driver in the investigations discussed below was a conventional Foster-Seeley type of discriminator used in conjunction with the usual rectifier diodes (6H6), preceded by a 6AC7 pentode employed as a saturated amplifier to produce amplitude limiting. Since considerable data were already available concerning f-m signal depression or capture with limiting (1), it was considered desirable to obtain data segregating the capture inherent solely in the f-m detector alone. It was therefore necessary to convert the 6AC7 stage from a limiter into a relatively linear buffer-amplifier as shown in Figure 13.

The following modifications (see Figure 13) were made to the circuit of the 6AC7 (V-7) driver stage to render it relatively linear over the desired signal-input range. Resistor,



Input to grid of 6AC7 (V-7) through .01 MF condenser
(V-7) converted from limiter to buffer amplifier.
Input signal modulated 22.5 kc at 2000 cps.
Input carrier frequency centered at discriminator
center frequency = 5250 kc.

Figure 23 - F-m detector transmission characteristic (including buffer pre-amplifier)

R-30, A 22,000-ohm screen and plate dropping bleeder resistor was removed. The plate and screen voltage was increased from somewhat under 70 to about 120 volts. A three-volt bias battery was used in the grid return circuit, and the cathode was left directly at ground potential. The buffer stage then responded almost linearly to input amplitude variations up to about 1 volt carrier input level.

The transmission characteristic of the modified pre-amplifier and f-m detector circuits is shown in Figure 23. No tendency to saturate or limit is evident at any point below about 1 volt carrier input (60 db above 1 millivolt). The general shape of the characteristic resembles that of the a-m detector shown in Figure 14. A somewhat gradual transition from square-law to linear-law operation is apparent around an input level of 12 db above 1 millivolt.

The pass-band of both the a-m and f-m detector circuits considered in this report was at least 200 kilocycles wide between points of 6-db attenuation. Hence with the low modulation frequencies and relatively small frequency separation between carriers (less than 5 kc) prevailing in these investigations of common-channel interference, the effect of the selective circuits can be virtually disregarded. The static discriminator characteristic of the f-m detector used is shown in Figure 24. A bandwidth of linear response of almost 200 kc is obtained and the peak-to-peak bandwidth is 290 kilocycles. The characteristic shown in Figure 24 is considered satisfactory for the purpose intended. An additional dynamic check upon discriminator linearity is shown in Figure 25. Linearity is excellent from less than 10 kc deviation up to 100 kc.

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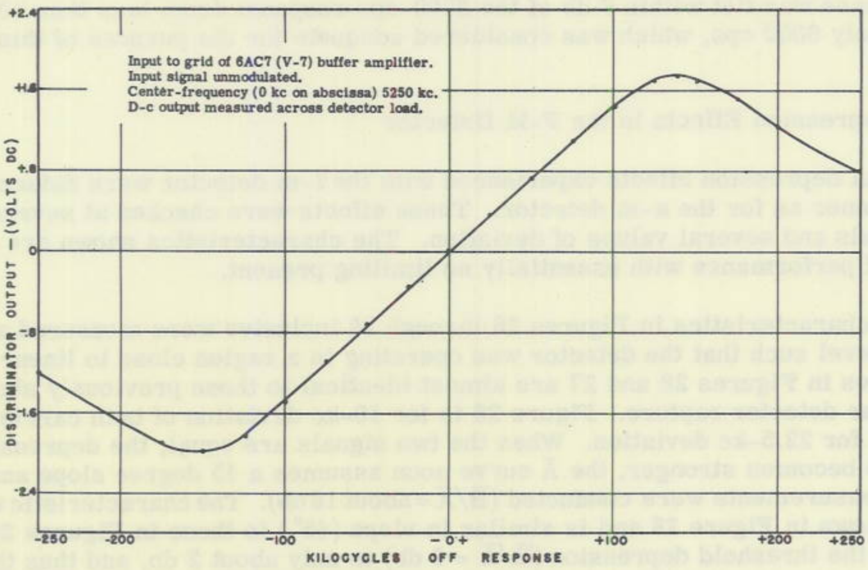

Figure 24 - Static discriminator characteristic of f-m detector

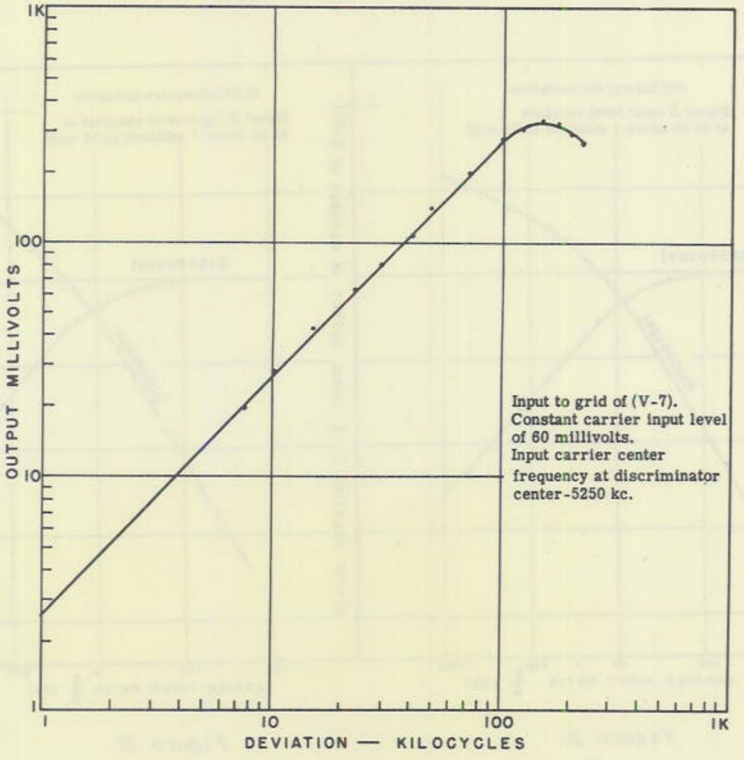

Figure 25 - F-m detector modulation characteristics

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Several additional characteristics were measured with one signal input. The most important for this study was the audio-frequency response of the detector. Without pre-emphasis in the signal generator or any intentional de-emphasis in the detector circuits, the response was flat within 6 db of the 2000-cps response from less than 50 up to approximately 6000 cps, which was considered adequate for the purpose of this investigation.

Signal Depression Effects in the F-M Detector

Signal depression effects experienced with the f-m detector were determined in the same manner as for the a-m detector. These effects were checked at several detector-input levels and several values of deviation. The characteristics shown are considered typical of performance with essentially no limiting present.

The characteristics in Figures 26 through 28 inclusive were measured at an input carrier level such that the detector was operating in a region close to linear-law response. The curves in Figures 26 and 27 are almost identical to those previously shown illustrating a-m linear detector capture. Figure 26 is for 10-kc deviation of both carriers; that in Figure 27 is for 22.5-kc deviation. When the two signals are equal, the depression of $\bar{A}$ is 3.5 db. As $\bar{B}$ becomes stronger, the $\bar{A}$ curve soon assumes a 45 degree slope and retains it as far as measurements were conducted ($\bar{B}/\bar{A}$ = about 18 db). The characteristic with 50-kc deviation is shown in Figure 28 and is similar in slope (45°) to those in Figures 26 and 27, except that the threshold depression ($\bar{B}/\bar{A} = 0$ db) is only about 2 db, and thus the total depression is somewhat less over-all. This effect may possibly be due to noncentering of the f-m signal on the discriminator characteristic of Figure 24. The effect was not observed in the over-all system capture measurements (1), and theoretically capture should be unaffected by the bandwidth of modulation (17).

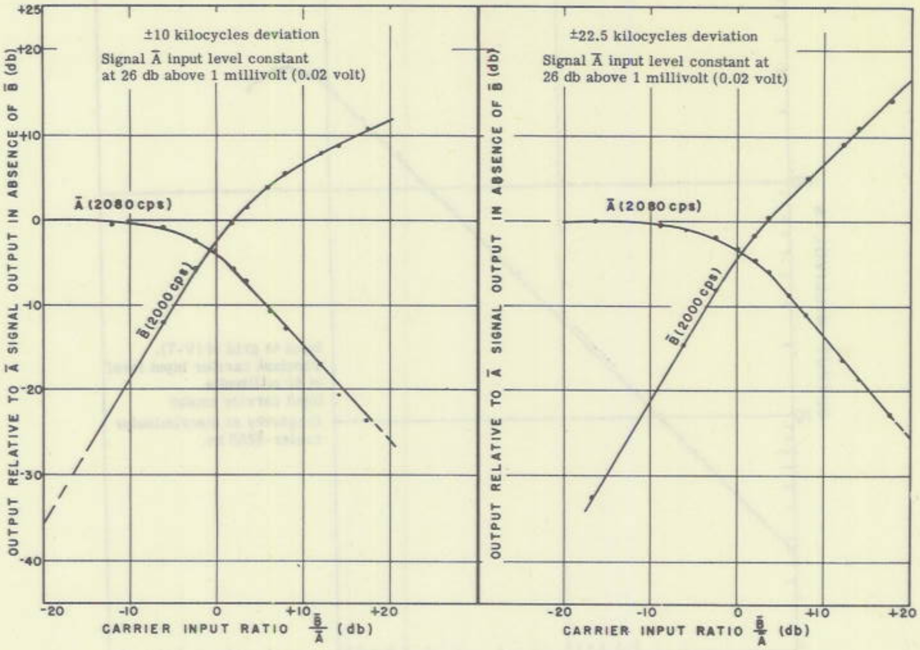

Figure 26 *Figure 27*

Depression of the weaker signal in the output of an f-m detector

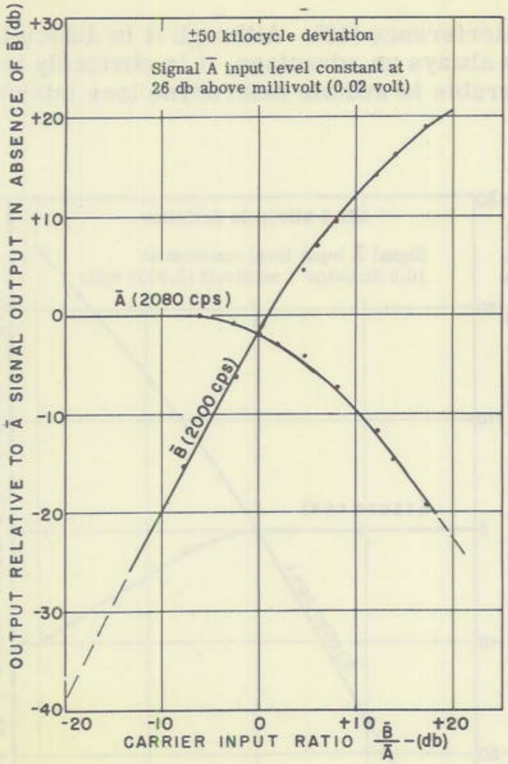

Figure 28 - Depression of the weaker signal in the output of an f-m detector

It is to be expected that the f-m detector, like the a-m detector, will provide less depression of the weaker signal in the region of square-law response (1,17). This is confirmed by the data given in Figures 29 and 30. The characteristic for the a-m detector under comparable conditions was shown in Figure 15. From the data shown in Figures 26 through 30, it is apparent that the capture attributable solely to the rectifiers of an f-m detector is very similar to that attributable solely to an a-m detector-rectifier.

The Heterodyne Output from an F-M Detector

The problem of heterodyne interference in FM is decidedly different from that in AM, although its significance as regards common-channel performance is equally great. In a-m reception when two received carriers are separated by a frequency within the pass-band of the receiver, reproducer, and the listener, a heterodyne which is fixed in frequency is apparent, accompanied by various cross-products. With f-m reception, such a fixed-frequency heterodyne is apparent only when both received carriers are unmodulated. When either or both carriers are modulated, the fundamental heterodyne frequency varies by an amount determined by the relative deviation of the two carriers.

Frequency modulation thus offers possible advantages under some conditions in regard to heterodyne interference. When either or both of the co-channel carriers are deviated considerably beyond the audio pass-band of the listener, reproducer, or receiver, the heterodyne will remain undetectable a portion of the time. Thus the use of wide deviations, such as in broadcast FM, reduces the relative intensity of heterodyne interference considerably. Of course, wider deviation adds the disadvantage of requiring more bandwidth and frequency spectrum for a single signal. It is, in addition, likely to exhibit greater output distortion effects than are encountered with narrow deviation. The use of high deviation ratios, such as 5 to 1, is so interesting as a means of heterodyne reduction that one author has stated that this, not greater capture effect, is the chief "advantage" of FM in common-channel interference (18). Although it is difficult to agree with the assumption that greater capture is always an advantage, it is obviously true that a wide-band f-m system will be less vulnerable to audible heterodyne tone interference than a narrow-band system.

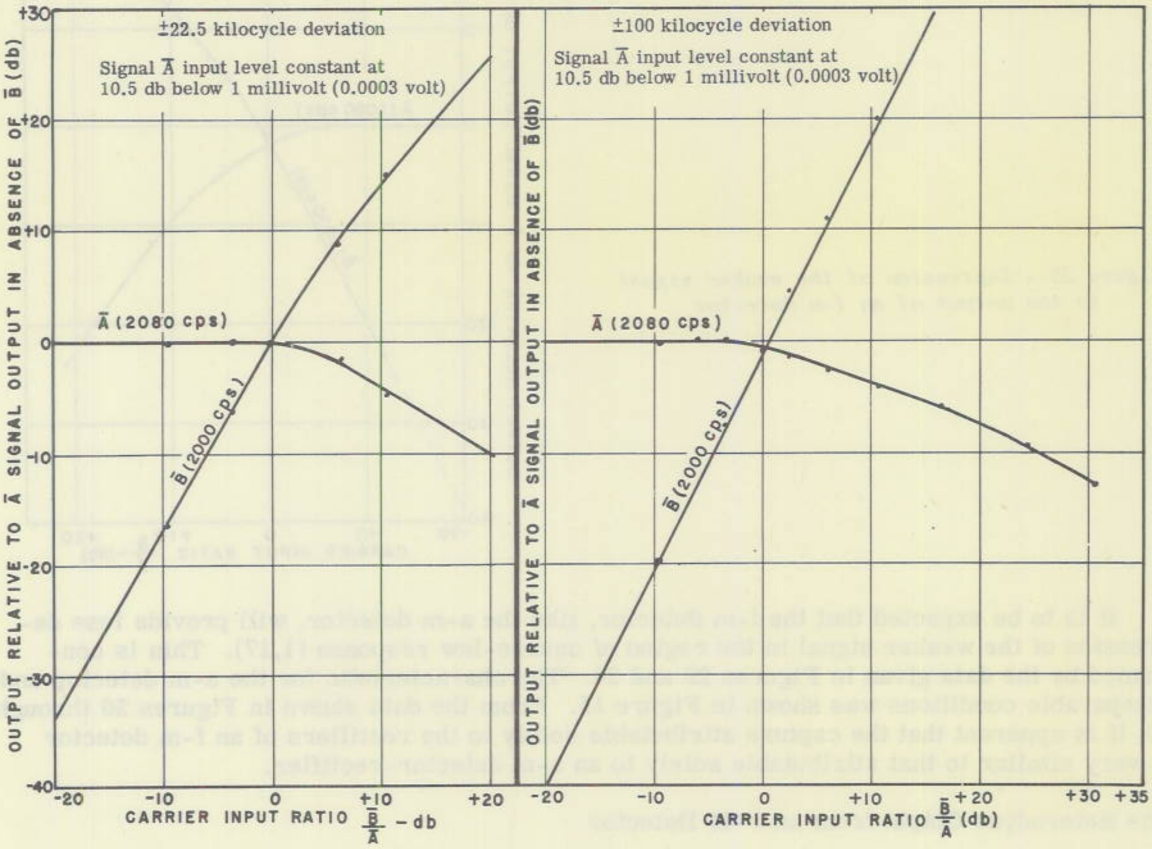

Figure 29 *Figure 30*

Depression of the weaker signal in the output of an f-m detector

There are, however, some grave disadvantages to FM as regards heterodyne in common-channel operation. It has previously been stated that with FM the heterodyne tone is doubly modulated in frequency by two f-m signals. As a result, any audible heterodyne has a most annoying "swishy" or "spitting" sound. Although some authors have described this characteristic as being "more detrimental" than the steady heterodyne tone with AM (Reference 17, page 38), it is a factor which has apparently not been given sufficient weight in most comparison studies of f-m and a-m systems. This annoying characteristic was encountered in the recent NRL comparison trials between AM and narrow-band f-m systems (4,5). It is believed to have been a major contributing factor to the superiority of AM during common-channel intelligibility tests. These tests were made with an f-m system employing a low modulation index, but the psychological handicap that FM with its varying heterodyne presents as compared to AM with a steady tone cannot be contravened. The Harvard Psycho-Acoustic Laboratories have found in tests that a warbling tone was much more effective as a jamming device than a steady tone (19).

Since the frequency of the f-m heterodyne tone when either or both of two co-channel signals are modulated is constantly varying, heterodyne measurements of the f-m detector similar to the wave-analyzer tests of the a-m detector could not be made under modulated conditions. A heterodyne measurement with two unmodulated carriers, separated from each other by 1000 cycles, was made and is shown plotted in Figure 31. It is seen that the results in this case (Figure 31) are similar to the heterodyne output values obtained with a linear a-m detector, as previously shown in Figures 19 and 20. This result is verified by several authors (20).

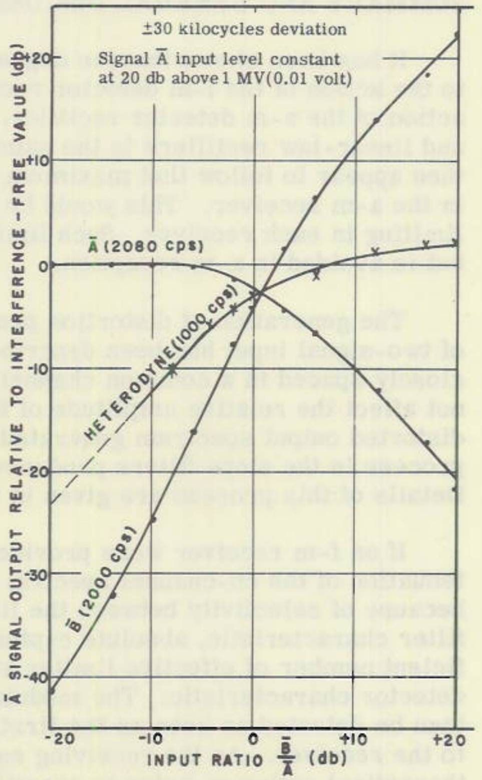

Figure 31 - Heterodyne in f-m detector

Regardless of the deviation employed, the amplitude of the heterodyne envelope will be maximum with respect to signal energy when the carrier-input ratio of the two signals is unity. Whenever the carrier input ratio is less than -3 to -6 decibels, the amplitude of the heterodyne will vary directly as the product of the two input-carrier levels. In other words, its slope as plotted in this report will be 45 degrees when $\bar{B}/\bar{A} < 1$. This is asserted in several places in the literature (21). The peak over-all output amplitude of the beat-note (at unity signal-input ratio) is reduced by wide-band modulation which exceeds the post-detector pass-band in the ratio of the output cut-off frequency over the maximum deviation (21). In other words, if the deviation is increased to ten times the post-detector bandwidth, the heterodyne output over-all will be reduced by a factor of 20 db. The slope of the beat-note output with changing signal-input ratios will, however, remain constant. This is confirmed to some extent by the capture data secured during the recent a-m vs. f-m trials with 6- and 40-kc deviation (Reference 3, Figures 26 and 27).

On a strictly amplitude basis, the f-m system will have an advantage over the a-m system in regard to heterodyne interference amplitude when the deviation ratio exceeds unity. When the reverse is true, it is said that AM will have an advantage (22). The statement that the f-m system will have an "advantage" at deviation ratios in excess of unity neglects a very important factor, however, namely that the f-m beat-note is of an interrupted, warbling character. A listener can mentally discriminate, to some extent, against the steady beat-note in AM, but discrimination is not possible in FM. This psychological disadvantage of FM undoubtedly makes the intelligibility equality of the two systems (in regard to heterodyne interference) occur at deviation ratios in excess of unity.

SUMMARY AND GENERAL DISCUSSION

It has been shown that the degree of the weaker-signal depression attributable solely to the action of the f-m detector rectifiers is identical to that attributable solely to the action of the a-m detector rectifier. The difference in performance between square-law and linear-law rectifiers is the same in the f-m case as it is in the a-m case. It might then appear to follow that maximum capture in the f-m receiver would be identical to that in the a-m receiver. This would be substantially the case in the absence of pre-detector limiting in each receiver. Such limiting, however, is essential for good f-m performance, but is avoided in a-m reception.

The generation of distortion products in the output circuit of a limiter under conditions of two-signal input has been described. Assuming that the input signals are all relatively closely spaced in a common channel, the receiver pre-detector selectivity normally will not affect the relative amplitude of the original signals or their sidebands. However, the distorted output spectrum generated by subsequent limiting and the resultant cancellation process in the slope filters produces the greater capture experienced with f-m receivers. Details of this process are given in the main capture report (1).

If an f-m receiver were provided with (1) ideal effective limiting, (2) no relative attenuation of the co-channel spectral component in the output of such limiting circuits because of selectivity between the limiter and detector, and (3) a perfectly linear slope-filter characteristic, absolute capture (90° slope) might be approached, provided a sufficient number of effective limiter stages were used and the receiver had a linear-law detector characteristic. The modulation of one signal to the exclusion of the other could then be detected as soon as the first signal was even very slightly the stronger at the input to the receiver. As the receiving equipment or operating conditions deviate from this theoretical optimum owing to practical limitations, the degree of capture will be reduced. In the absence of limiting of any sort prior to detection, the degree of capture in an f-m system is essentially the same as that in an a-m system, assuming both systems are otherwise equivalent (i.e., both have linear-law detector-rectifiers, and there is no AVC operating in the a-m system; or both have square-law detector-rectifiers with no AVC in the a-m system).

The amplitude of the heterodyne output in unmodulated f-m reception follows essentially the same law as governs the heterodyne output in a-m reception. The characteristics of the f-m heterodyne, however, are of greater significance in regard to intelligibility. In a wide-band f-m system, the peak amplitude of the heterodyne is reduced by the ratio of the output cutoff frequency over the maximum deviation. This offers possible advantages to the wide-band f-m system, but the fact that the f-m heterodyne beat-note is itself deviated is disadvantageous. The fluctuating tone of the f-m beat-note during modulation is far more distracting than its steady a-m counterpart.

CONCLUSIONS

It is concluded that:

A. The depression of desired signal output due to the presence of an interfering carrier is the same in both a-m and f-m detector rectifiers having the same law of rectification.

B. The limiters used in f-m reception produce output distortion components which contain signal information. A wide-band discriminator circuit is necessary to retain as much of this information as possible.

C. With the f-m signals present, cascaded limiters of good design and a wide-band discriminator are necessary to insure that the signal which is even very slightly the stronger will control receiver output.

D. Perfect f-m capture, resembling on-off switching, can be approached only with a large number of cascaded limiter stages, a wide-band discriminator, and linear-law rectifiers.

E. Heterodyne beat-note output from both a-m and f-m systems, under conditions of no modulation, varies in amplitude in essentially the same way and with about the same values as a function of undesired-to-desired carrier amplitude ratio.

F. Modulation of one or both carriers produces no change in beat-note amplitude or pitch in a stable a-m system, so that it is feasible to filter out the beat-frequency output in such a case.

G. Modulation of one or both carriers in an f-m system produces complex variations of beat-note pitch, resulting in a swishing, spitting type of interference with a high annoyance value. When the frequency-deviation exceeds the audio or output circuit cutoff frequency, the beat-note will fall outside the output bandwidth part of the time. It may, however, produce transient disturbance effects as it traverses the cutoff region, thereby nullifying some of the improvement in this latter case.

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