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INTERFERENCE SUPPRESSION PERFORMANCE OF SEVERAL FM RECEIVERS USING FEEDFORWARD

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INTERFERENCE SUPPRESSION PERFORMANCE OF SEVERAL FM RECEIVERS USING FEEDFORWARD

by

BEN H. HUTCHINSON, JR.

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ABSTRACT

The feedforward signal-cancellation technique is based on subtractively combining the outputs of limiters and linear amplifiers having a common input. Used in an FM receiver, feedforward provides an attractively simple and effective method for suppressing interference to an FM signal from other co-channel or adjacent-channel signals which may be either weaker or stronger than the desired signal. The thesis explores theoretically and experimentally the potential performance and inherent limitations of practical FM receivers using feedforward. Design criteria are discussed for various interference conditions and the relative merits of several practical feedforward circuits are considered.

A laboratory model FM receiver was built and tested with three different feedforward circuits, its performance being measured under a variety of interference conditions. Significant improvement in the stronger-signal capture performance of a mediocre FM demodulator was demonstrated. Sinusoidal modulation was recovered from FM signals between 0.05 and 0.9 times the amplitude of an interfering signal on the same channel, distortion ranging generally between 8 per cent and 30 per cent for various interference conditions. Completely intelligible speech modulation was also recovered from the weaker of two co-channel FM signals. Numerous suggestions for further work are given.

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CHAPTER 1

INTRODUCTION AND BACKGROUND

The feedforward signal-cancellation technique, applied to an FM receiver, allows capture of a desired FM signal in the presence of an interfering signal which may be either weaker or stronger than the desired signal at the receiver input and whose frequency occupancy may be quite close to or even within the channel occupied by the desired signal.

The idea for the technique was conceived by E. J. Baghdady as a by-product of his theoretical investigation of the FM interference-suppression properties of narrow-band amplitude limiters. Several detailed accounts of this work have been published;[1, 2, 3, 4] hence, the complex mathematical analysis involved will not be repeated here. The assumptions involved and the conclusions which suggested the feedforward idea will be briefly summarized.

In his analysis, Baghdady assumes an ideal amplitude limiter, defined as a device which delivers a constant output voltage amplitude so long as the amplitude of its input signal is above a certain minimum, E_{thresh}. (See Figure 1). In operation, the instantaneous amplitude of the input signal is maintained above E_{thresh} at all times. An ideal bandpass filter is assumed to follow the ideal limiter, its bandwidth being small relative to its center frequency (Figure 2). Two FM signals

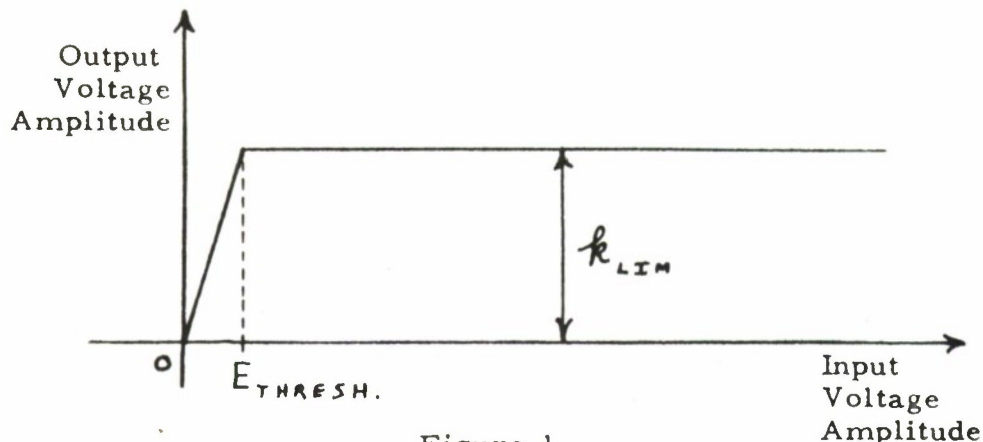

Figure 1

Transfer Characteristic of Ideal Amplitude Limiter

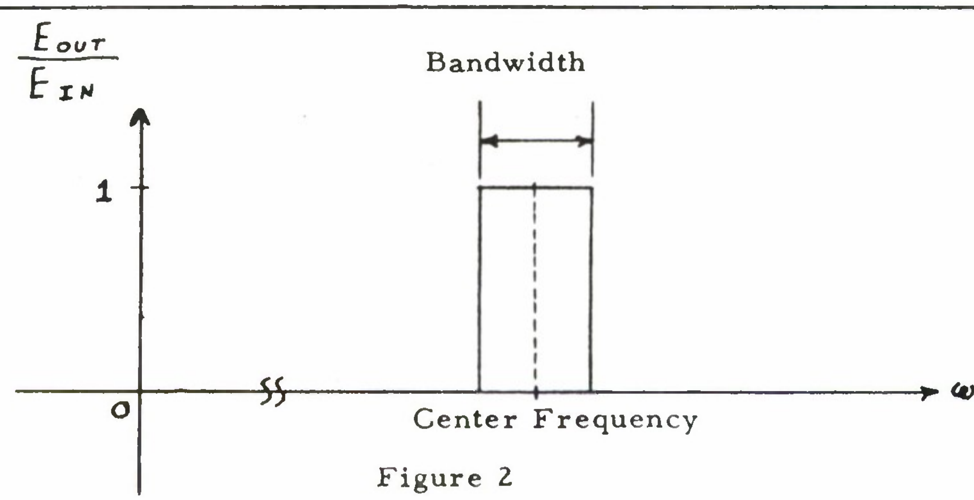

Figure 2

Frequency Characteristic of Ideal Bandpass Filter For $\omega > 0$.

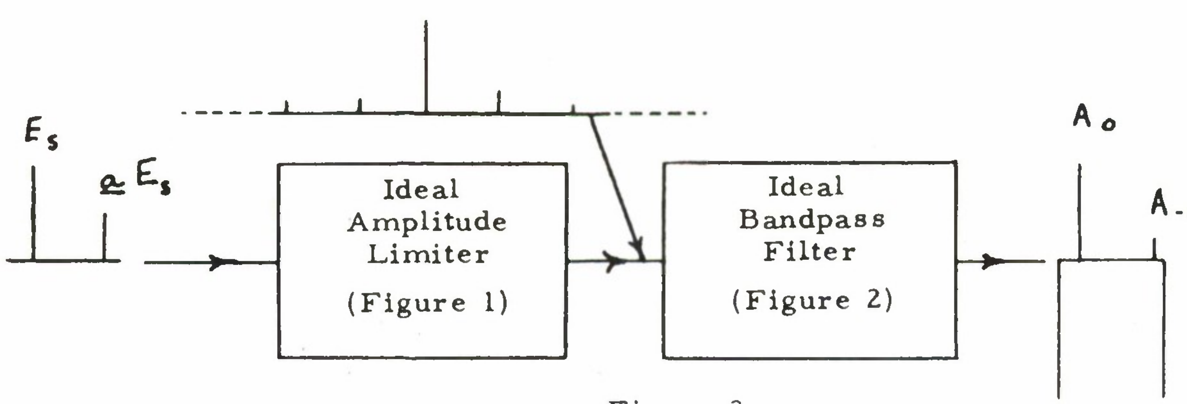

Figure 3

Ideal Narrow-Band Limiter with Two-Signal Input having normalized amplitudes 1 and $\underline{a}_{in}$ and center frequencies within the filter passband are assumed at the limiter input. The quantity $\underline{a}_{in}$ is, of course, the ratio of weaker-signal amplitude to stronger-signal amplitude, and, in applications in which the stronger signal is the desired one, has been called the "input interference ratio". For purposes of computation, the so-called "quasi-static" analysis [5] is applied; i. e., the modulation on the FM signals is assumed to be slow enough relative to their center frequencies and frequency difference so that over several cycles of the difference frequency the two signals can be treated as two stationary carriers. Thus, the analysis starts with two carriers of frequencies p and p + r, $r \ll p$, and amplitudes 1 and $\underline{a}_{in}$, $\underline{a}_{in} < 1$, fed to the input of an ideal narrow-band limiter (See Figure 3). The purpose of the analysis was to determine the character of the signal at the output of the limiter under various interference conditions and for various bandwidths of the post-limiter filter. The filter bandwidth is for convenience expressed in units of one I. F. bandwidth (BW_{if}), this being, of course, the minimum bandwidth necessary for reproducing the modulation of the desired signal in a practical system.

The non-linear action of the limiter produces many new frequency components above and below the two input signal frequencies. These components are spaced apart by the frequency difference r. An exact Fourier analysis of this complex limiter output signal reveals that the ratio $\underline{a}_{out}$,

$$\text{where } \underline{a}_{out} = \frac{\text{amplitude of component at frequency } p + r}{\text{amplitude of component at frequency } p},$$

is less than the corresponding input ratio $\underline{a}_{in}$. The amount of this

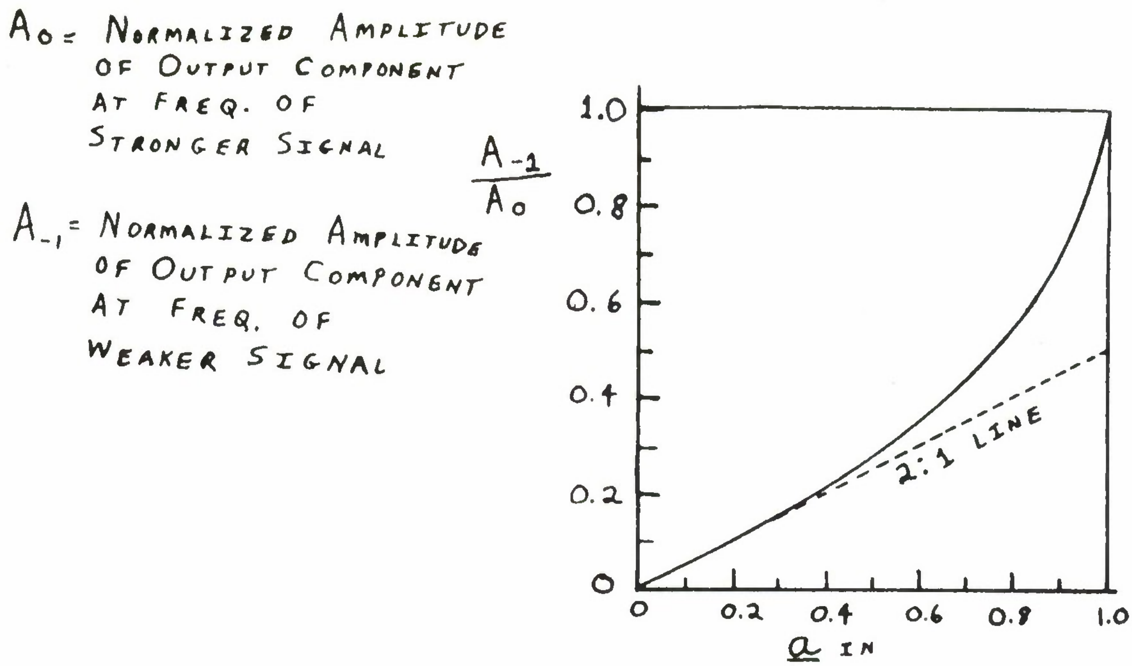

Figure 4

Effect of Narrow-Band Limiter in Reducing Interference Ratio, Considering Only the Two Output Components at the Input Signal Frequencies

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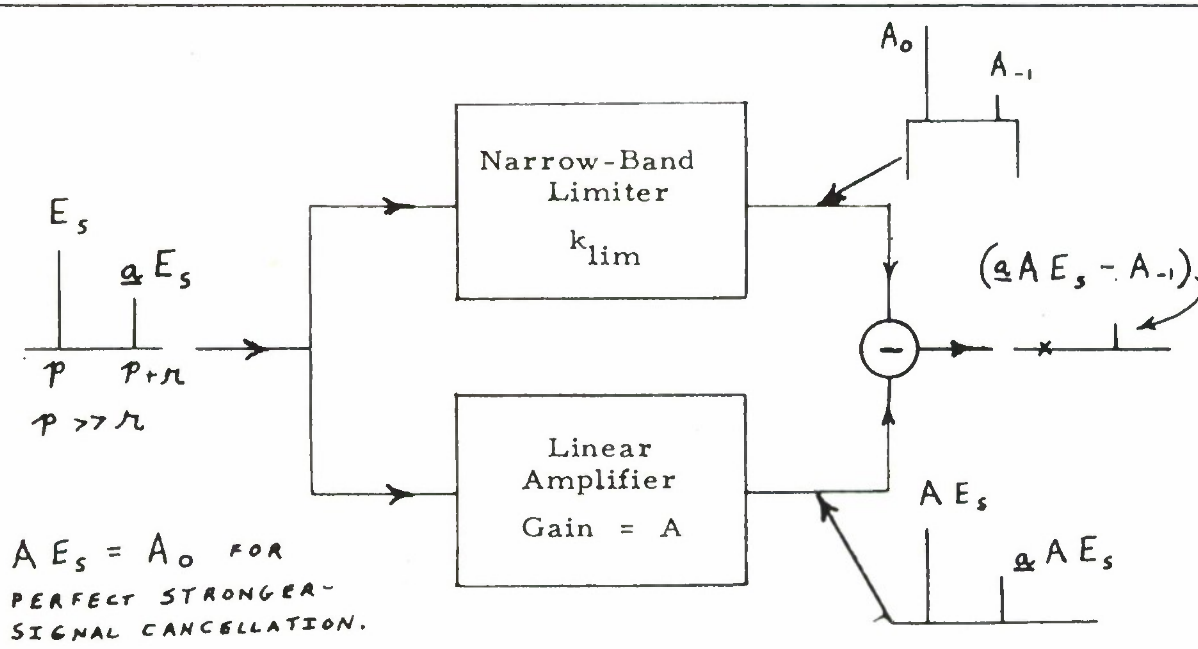


Figure 5

The Basic Feedforward Circuit.
An Example of Stronger-Signal Cancellation is Shown.

reduction is given in Figure 4. For an $\underline{a}_{in}$ of 0.5 or less, $\underline{a}$ is reduced by a factor of approximately 2, or about 6 db.

If the limiter filter is BW_{if} wide and the frequency difference r is greater than $BW_{if}/2$, only two components will appear at the filter output, those at the frequencies of the two input signals. The limiter thus accomplishes a reduction in the amplitude of the weaker signal relative to that of the stronger with no "side effects" for $r > BW_{if}/2$. If $r < BW_{if}/2$, additional components are passed by the filter and the picture is more complex; however, detailed analysis shows that the net effect is beneficial reduction in interference from the weaker signal for $\underline{a} < 0.863$. Limiter bandwidth must be increased to obtain beneficial interference reduction for $\underline{a} > 0.863$. Theoretical demonstration of this interference reduction and derivation of minimum allowable limiter filter bandwidths constituted the main purposes of the analysis.

The idea for the feedforward technique [6] arose from the observation that if two FM signals occupied the same channel or adjacent channels, a narrow-band limiter could easily be arranged such that the instantaneous frequency difference r would be greater than half the limiter bandwidth over a significant portion of the modulation cycle. Over this portion of the cycle, the limiter would have no other effect than reducing the amplitude of the weaker signal relative to that of the stronger, the amount of the reduction being given by Figure 4. If the two signals fed to the limiter are also fed to a linear amplifier (Figure 5), their relative amplitude in the amplifier output will, of course, be the same as that at the input. If the outputs of the two parallel channels are combined subtractively with correct relative amplitudes, either the weaker or the stronger signal can be completely cancelled, leaving a residual output at the frequency of the other signal. Figure 5 shows an example of cancellation of the stronger signal. The technique derives its name from the fact that signals are "fed forward" around the limiter through the linear amplifier.

When r is less than $BW_{if}/2$, the situation is more complex, since more than two components pass the limiter filter. However, if the limiter-amplifier combination is followed by a high capture-ratio FM demodulator, the weaker signal can be captured as long as the average frequency of the resultant of all of the passed components equals the frequency of the weaker-signal component. When a number of extra components are admitted, this condition is, in general, no longer satisfied and weaker-signal capture fails. Thus, weaker-signal capture is possible only over part of the modulation cycle. If, however, the circuit is adjusted for <u>suppression</u> of the weaker signal, the average frequency of the resultant signal at the output of the feedforward circuit will always equal the frequency of the stronger signal. Thus, stronger-signal capture is possible over the entire modulation cycle.

In the analysis,[6] a parameter K is defined as $\frac{A E_s}{k_{lim}}$,

in which

	A	=	feedforward amplifier gain
	E_s	=	input signal amplitude to limiter and amplifier (stronger-signal amplitude for two signals)
	k_{lim}	=	constant output signal level of amplitude limiter

Physically, K is the ratio of the linear-channel output to the limiter output for a single unmodulated carrier input. Negative values of K correspond to 180° phase difference in the two channel outputs, resulting in subtraction. For values of K near -1, the stronger signal will be nearly or completely cancelled, allowing the originally weaker signal to predominate in the output. Values of K in the neighborhood of -0.5 to -0.7 result in suppression of the weaker signal. Reduction in interference from a weaker signal equivalent to that obtainable from several stages of narrow-band limiting is possible.

The theoretical analysis by Baghdady outlined above predicts that a feedforward using a good narrow-band limiter (approaching the ideal) can cause the weaker of two co-channel FM signals at its input to predominate at its output as long as sufficiently few additional components pass the limiter filter. The analysis also predicts that weaker-signal capture will be lost over part of the modulation cycle, since part of the time the average frequency of the resultant output signal will not equal the frequency of the weaker-signal component.

Previous Experimental Work

Several experimental investigations of feedforward circuits have been completed or are presently in progress; however, only two accounts of such work have so far been published, i.e., the S. M. theses recently completed at M.I.T. by R. H. Small(7) and R. G. Griffin(8). Unfortunately, both of these investigations were concerned with specific application of the feedforward technique to fairly complex systems at a time when no proven circuit design existed. In order to carry out their thesis plans, it was necessary in both cases to quickly freeze a circuit design, build several copies, incorporate them into a complex system, and make a number of measurements. Time was not available to go deeply into the workings of the circuit or to optimize its performance. However, Small and Griffin did succeed in demonstrating that their particular feedforward circuits were capable of improving the stronger-signal capture capabilities of a demodulator of mediocre performance and of recovering weaker-signal modulation with quality ranging from poor to excellent, depending on whether the two signals occupied contiguous or overlapping channels. They were unable within the limits of their thesis plans to devote sufficient effort to the problems of operational feedforward circuitry; to explore the many different ways of realizing the basic block diagram of Figure 5; to investigate the practical limitations on the interference suppression performance obtainable with simple feedforward circuits, including the effects of the performance of other portions of the receiver; or to explore the effects of arbitrarily varying the modulation frequency on both desired and interfering signals.

Purpose of Present Investigation

There are several ways to realize the basic block diagram of Figure 5 in the laboratory. Different types of limiters are available; moreover, a cascade of several limiters may be used instead of the single limiter indicated in Figure 5.

The necessary phase opposition at the two channel outputs may be obtained by several different combinations of grounded grid, grounded cathode, and cathode follower circuits or by using a center-tapped transformer or some other phase-splitting means.

In the present investigation, an attempt is made to investigate both theoretically and experimentally several of these different circuits and to measure their performance under a wide variety of interference conditions, the primary purposes being: (1) to gain sufficient understanding of the feedforward technique to be able to formulate a few general principles to guide the designer of FM receivers using feedforward; (2) to gain some idea of the sort of signal-capture performance potentially available from a feedforward-equipped receiver; (3) to discover some of the fundamental limitations of the technique, and some of the problems involved in applying it.

The body of the thesis report consists of six chapters: Chapter 2 is a general discussion of some of the basic problems encountered in designing an FM receiver using feedforward. Chapter 3 presents the advantage and disadvantages of several specific types of feedforward circuits. Chapter 4 contains a description of the design and functioning of the experimental equipment built for the investigation. Chapter 5 presents the results of experimental interference tests, with interpretations. Chapter 6 contains the over-all conclusions, while Chapter 7 is devoted to suggestions for further work. The list of suggestions is quite long because of the exploratory and problem-defining nature of the study.

Both the theoretical and experimental portions of the study are "use-oriented" in the sense that these questions are constantly raised:

(1) Will the feedforward technique be useful in an existing or presently conceivable FM system?

(2) Does it offer any net advantages over competitive signal-processing techniques?

(3) What basic engineering problems must be solved in the development of a workable, operational FM receiver using feedforward?

CHAPTER 2

PROBLEMS ENCOUNTERED IN PRACTICAL FEEDFORWARD SYSTEMS

The basic feedforward system of Figure 5, Chapter 1, may be used with a good FM demodulator to capture either the weaker or the stronger of two competing FM signals. The signals may occupy the same channel ("co-channel" signals) or adjacent, non-overlapping channels. The requirements for optimum performance depend upon the particular interference situation; the various situations will therefore be considered separately.

Stronger-Signal Capture

As shown in Chapter 4, use of a feedforward circuit ahead of a mediocre FM demodulator can dramatically improve the ability of the demodulator to reject interference from a co-channel signal only slightly weaker than the desired signal. Furthermore, the requirements on the components of the feedforward (limiters, bandpass filters, amplifiers) are less critical than for the case of weaker-signal capture. A feedforward will usually outperform a simple limiter in reducing weaker-signal interference, if it works at all. Small[7] demonstrated dramatic improvement in stronger-signal capture performance with feedforward circuits which had many shortcomings.

When adjacent-channel interference weaker than the desired signal is involved, the generalizations given above still hold, provided only that the limiters in the system are sufficiently fast-acting to cope with the amplitude disturbance associated with the maximum frequency difference r and the interference ratio a to be encountered[3]. The interference need not be weaker than the desired signal at the receiver input as long as the receiver front end and I. F. amplifier are selective enough to insure that the interfering adjacent-channel signal is always weaker at the feedforward input.

Methods other than feedforward are available for achieving excellent stronger-signal capture: the wideband approach[4, 12], the use of cascaded narrow-band limiters[4], and the use of an oscillating limiter[13]. The wideband method is usually so expensive and complicated as to be obviously inferior to the other schemes. An oscillating limiter is substantially equivalent to a feedforward in circuit complexity, but is much more critical in adjustment. A chain of narrow-band limiters is more straightforward in design, construction, and alignment than a feedforward, since the problems of maintaining the correct value of K and of matching phase shift in limiter and amplifier channels are not involved. Very good capture performance can be obtained from a limiter chain and a moderately wideband discriminator, as shown in Chapter 4. In many applications, the potential improvement in capture performance obtainable by the use of feedforward instead of a limiter chain would not be worth the extra effort involved in realizing it.

The existence of the competitive alternate solutions discussed above, the relaxed circuit design requirements compared with those for weaker-signal capture, and the fact that excellent performance has already been demonstrated (reference 7 and Chapter 4) combine to make the problem of building better feedforwards for stronger-signal capture neither very interesting nor very challenging compared with the problem of weaker-signal capture, except as noted briefly in Chapter 7. For these reasons, little effort was devoted to the problem in this investigation, except that mentioned in Chapter 4.

Weaker-Signal Capture

An interfering signal stronger than the desired signal may be either adjacent-channel or co-channel. If an adjacent-channel signal is stronger at the receiver input, there are several possibilities. Arbitrarily good I. F. selectivity can reduce the problem to that treated above. If, however, the receiver front end and the I. F. amplifier are flat over the full frequency range covered by both signals so that the interference arrives at the feedforward input unattenuated, the feedforward technique can deal with it quite adequately under laboratory conditions. Demonstration of this fact was the major accomplishment of Small's thesis(7).

The I. F. amplifier must, however, fully include both signals in its passband for optimum weaker-signal capture; if the interfering stronger signal is on the "skirt" or sloping portion of the passband, its amplitude at the feedforward input will vary dynamically with modulation as its frequency rides up and down the sloping skirt. This may cause the interfering signal to be sometimes stronger than the desired signal and sometimes weaker, making any consistent adjustment of the feedforward impossible. Even if the I. F. characteristic is such that the interfering signal remains consistently stronger, the interference ratio $\underline{a}$ will vary over the modulation cycle, preventing an optimum adjustment for K, which varies with a; this is explained later.

Thus, it is necessary to employ an I. F. filter which passes the interference without attenuation in order to effectively utilize the weaker-signal capture capabilities of feedforward against a stronger adjacent-channel interfering signal. This technique is not an obvious choice; it seems a bit strange to make no use at all of I. F. selectivity to reject adjacent-channel interference. Great pains must be taken to obtain good weaker-signal capture performance, especially under field conditions, as explained later in this chapter. The problems involved are sufficiently important to raise serious questions as to whether or not a feedforward plus a wide I. F. filter offers any advantages over a straightforward steep-skirted I. F. filter in dealing with stronger adjacent-channel interference, even if it is necessary to go to the extreme of using a crystal or mechanical I. F. filter.

Capture of the Weaker of Two Co-Channel Signals

The only signal-processing techniques besides feedforward which allow capture of the weaker of two co-channel signals are the recently developed "dynamic trap" technique[6, 9] and its variation, the so-called "fixed trap" technique[6, 10, 11]. Both of these ideas are based on selectively reducing the amplitude of the stronger signal with a notch filter. In the dynamic trap, the notch dynamically tracks the stronger signal over the passband, while in a fixed-trap receiver the stronger signal is "frozen" in frequency by a mixing process, allowing the use of a fixed notch filter. Receivers using both techniques have shown good performance in the laboratory, especially the fixed trap receiver recently built by J. M. Gutwein[11]. Although the performance of this receiver is superior to that of any feedforward receiver built to date, feedforward is inherently much simpler than either trapping scheme.

Effective application of the feedforward technique to weaker-signal capture is thus an important problem, because of the attractive simplicity of the technique as compared with the only alternatives. The idea of weaker-signal capture in general is also interesting, partly because it was a problem generally considered insoluble until recently. A practical high-performance receiver capable of capturing either the weaker or the stronger of two co-channel FM signals would be extremely useful; it would allow an FM system to continue operation in the presence of intentional or unintentional interference from other systems using the same channel, even if the interfering signal was the stronger. This is an important extension in system capability. Such a receiver would also allow "stunts" such as multiplexing or simultaneous two-way transmission on a single channel.

The present investigation is primarily concerned with using the feedforward technique to capture the weaker of two co-channel FM signals, since this is both the most interesting and the most difficult problem connected with feedforward, as explained above.

Practical Requirements for Good Weaker-Signal Capture

A practical system patterned after the theoretical block diagram of Figure 5, Chapter 1, must meet several requirements if it is to deliver good weaker-signal capture performance:

(1) The limiter must approximate as closely as possible the action of the ideal narrow-band limiter described in Chapter 1.

(2) The components in the outputs of the limiter and amplifier at the frequency of the stronger input signal must be exactly equal in amplitude and exactly opposite in phase at all times to insure complete cancellation of the stronger signal.

(3) The feedforward amplifier must be linear.

The implications of these requirements and the problems of satisfying them in a practical system will be discussed separately.

(1) Problems of Practical Limiters

Three types of amplitude limiters have been used in previous practical FM systems: the pentode limiter, the diode limiter, and the gated-beam limiter (usually employing the 6BN6 tube). The salient characteristics of these three types differ somewhat; none satisfies completely the requirements for an ideal feedforward limiter. Good discussions of practical limiter problems are given in references 11 and 14.

The pentode limiter. Typical pentode limiters are shown in Figure 4, Chapter 4. The grid capacitor charges from the driving source and discharges through the grid resistor, clamping the positive peak of the R. F. input voltage at zero or at a slight positive voltage. The tube will conduct only over the portion of the cycle between zero grid voltage and cutoff; if input voltage is large enough, this time interval is approximately constant, and average plate current is essentially independent of input voltage amplitude. Screen and plate voltages are kept low to lower the grid cutoff voltage.

The pentode limiter is simple, cheap, and has no critical adjustments. It is probably the most widely used type of FM limiter. However, for feedforward use, it has serious disadvantages: the grid-circuit time constant $R_G C_G$ must be quite small for the limiter to cope with reasonably large values of a and frequency difference r, but it cannot be reduced indefinitely[3]. The grid capacitor must remain significantly larger than the tube input capacitance, and the grid resistor must remain much larger than the forward resistance of the grid-cathode diode. A low grid resistor also results in low input impedance, making the limiter hard to drive and hard to use with tuned circuits. Also, the limiter characteristic of a pentode limiter is usually gently rounded near the origin, so that its threshold is high, and has an inescapable slight upward slope instead of being perfectly flat. These disadvantages usually combine to make the simple pentode limiter a poor choice for use in a weaker-signal capture feedforward.

The gated-beam limiter. Figure 14, Chapter 4, includes a diagram of a gated-beam limiter stage using the 6BN6 tube. The operation of the limiter depends on the internal geometry of the 6BN6 tube. The electron stream is formed into a narrow beam which is "gated" by the control grid; the tube's plate current saturates when the control grid rises a few volts above cutoff.

The 6BN6 limiter has a reasonably low threshold, a higher input impedance than a low time-constant pentode limiter, and is free from the time-constant problem of the pentode limiter. By careful tube selection and bias voltage adjustment, an excellent limiter characteristic can be achieved with the 6BN6.

The outstanding disadvantage of the gated-beam limiter is that the characteristics of the one available tube, the 6BN6, vary over quite a wide range from tube to tube. Some tubes are inherently capable of better limiter performance than others, and observed performance varies over a wide range. Among the "good" tubes, the optimum bias voltages are different for each tube, requiring careful individual adjustment. Moreover, the tube has a nonlinear input impedance with a nonlinear reactive component, which disrupts tuned circuits to which the input is connected. McLaughlin(14) studies the 6BN6 in some detail; Gutwein(11) also studied gated-beam limiters.

The diode limiter. A very simple limiter can be made from two diodes biased to clip symmetrically. Semiconductor diodes are more convenient than thermionic types, and no bias is necessary if silicon diodes are used because of their 0.5 volt threshold before forward conduction. The basic limiter could hardly be simpler, and there are no time-constant problems and no adjustments. The performance available depends on diode characteristics, such as forward and reverse resistance and switching time.

The disadvantages of the diode limiter are two: no gain and very low input and output impedances. It is therefore usually necessary to use two tubes per limiter stage if tuned interstage filters are used; both tubes act as amplifiers, with the diode limiter between the amplifier stages. The diode limiter should be capable of excellent performance, if designed carefully and built with high-performance diodes. It has not been widely used in narrow-band applications, and further investigation is indicated, as noted in Chapter 7.

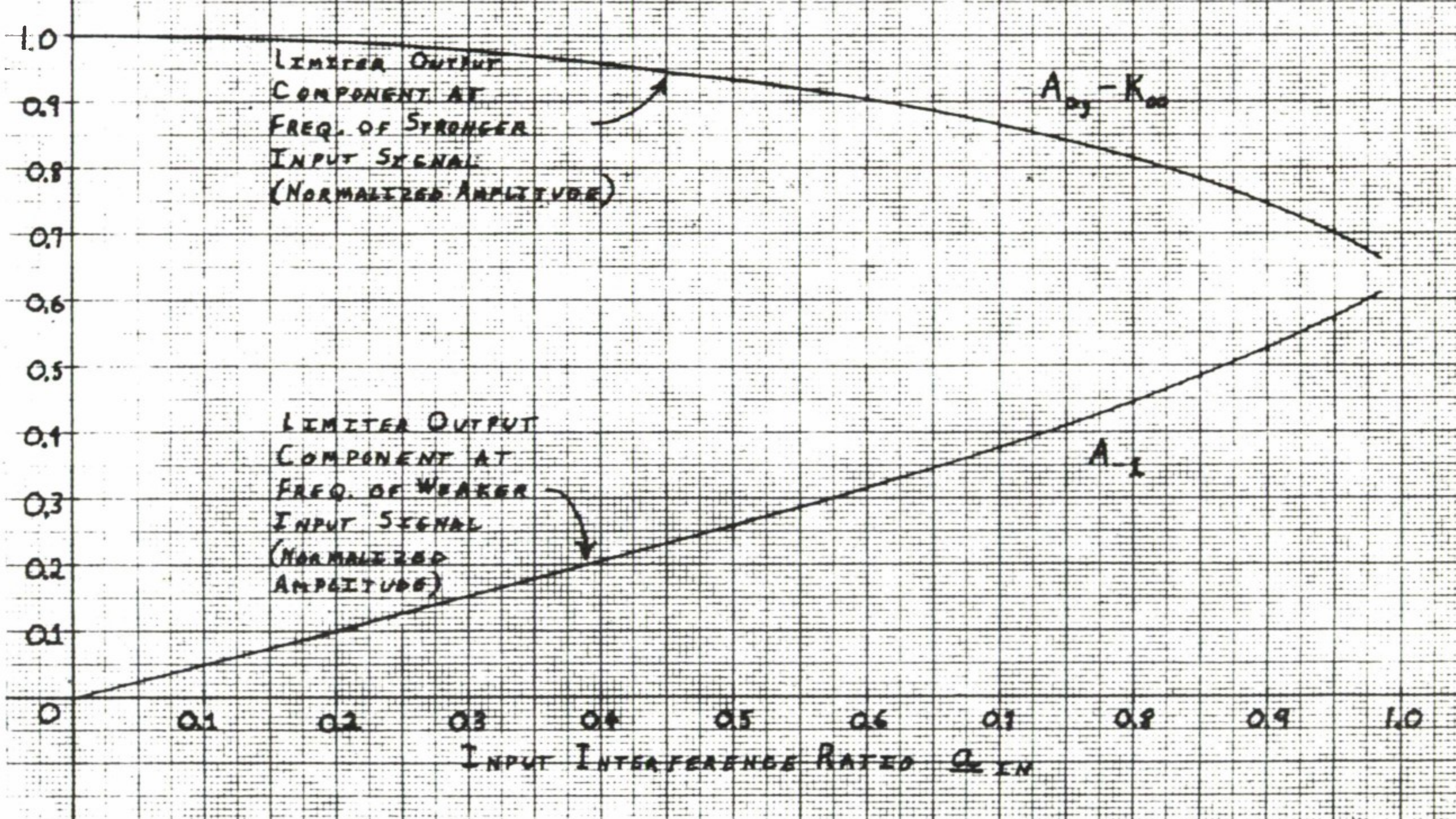
(2) Maintaining Accurate Interference Cancellation

A host of problems prevent perfect cancellation of the fundamental stronger-signal component in a practical feedforward circuit. Some would exist even with ideal system components, while others arise from equipment imperfections. The various disturbing influences will be discussed separately.

Variations in a. The results of Baghdady's analysis of the output spectrum of a limiter with two-signal input[1] show that even with constant stronger-signal amplitude at the limiter input, the amplitude of the fundamental stronger-signal component at the limiter output varies with a in a manner shown by Figure 1. Therefore,

Figure 1

Amplitude of Stronger and Weaker Signal Components at Limiter Output (A_o and A_{-1}) as a Function of a_{in}



even though the stronger signal amplitude at the feedforward amplifier input remains constant, the feedforward amplifier gain (and hence K) must vary with a to maintain perfect stronger-signal cancellation. The optimum value of K as a function of a is numerically equal to the normalized stronger-signal output amplitude (A_o) of Figure 1; this quantity is designated K_∞ and plotted by Baghdady[6].

Variations in Input Signal Amplitude. In the simple basic feedforward of Figure 5, Chapter 1, the amplitude of the stronger-signal component at the amplifier output obviously varies directly with the stronger-signal amplitude at the feedforward input. Cancellation is therefore perfect for only one value of input signal amplitude.

In previous experimental investigations of feedforward[7, 8], a narrow-band limiter was used ahead of the feedforward proper in an attempt to hold the feedforward input and hence amplifier output at a constant level, maintaining proper cancellation despite rapidly fluctuating stronger-signal amplitude. This end is achieved at a price: the threshold value of a below which worthwhile weaker-signal capture cannot be achieved is raised by about 6 db. This has been observed experimentally (see Chapter 5) and can be predicted theoretically, as follows: a weaker-signal feedforward receiver of even reasonable performance is capable of capturing the weaker signal down to at least $a = 0.5$. For $a < 0.5$, limiter requirements are not particularly severe (see Reference 3). Therefore, the theoretical reduction in a of 6 db is very closely approached by even a poor pre-limiter. This means, of course, that the value of a below which the system becomes useless is effectively doubled by the use of a pre-limiter. Or, for a specified threshold value of a, allowable tolerance on circuit components is effectively halved by use of the pre-limiter, as explained later. This difficulty is usually not serious, if a threshold no lower than a = 0.1 or 0.2 is desired.

A second source of trouble with the pre-limiter system is the difficulty of building a one-stage limiter of good enough performance (flat enough limiter characteristic) to maintain a high degree of constancy in the input signal amplitude to the amplifier, as brought out earlier in this chapter. Any irregularities in the performance of the pre-limiter will adversely affect the capture characteristic of the system. Therefore, in a high-performance system the pre-limiter must be designed and constructed very carefully. Even with an ideal pre-limiter, the optimum value of K is still a function of a (see Figure 6 of reference 6).

When the fluctuations in input signal level are sufficiently slow, there are two alternative solutions to the problem which avoid the threshold degradation of a pre-limiter at the cost of increased complexity. One way is to use a slow-acting pre-limiter; i.e., a limiter with a time constant which is long compared to the slowest important variation in input signal level due to modulation or inter-signal interference but fast enough to compensate for "long-term" variations in input signal strength. In ramified form, this suggestion grows into a sophisticated AGC system of high performance but long time constant, which controls the gain of everything ahead of the feedforward. Such a scheme should compensate for slow variations in input signal level without reducing the interference ratio at the feedforward input and thereby raising the threshold value of a.

The other method of avoiding the pre-limiter when slow signal level variations are encountered, also offers potentially better performance at the price of increased complexity. The idea is to use an over-all feedback control system which would automatically adjust the gain of the feedforward amplifier to minimize distortion in the captured weaker-signal message at the demodulator output. Such a system would compensate for variations in feedforward limiter output level and amplifier gain due to supply voltage, temperature variations and component aging and for the variation in the optimum value of K for different a and different degrees of modulation. The range of allowable input signal amplitude variation would be limited only by the dynamic range of the I. F. amplifier and feedforward limiter and the range over which the feedforward amplifier gain could be controlled automatically. A suggested design for such a system is given in Chapter 7.

Limiter Imperfections. Any departure of the feedforward limiter characteristic from the ideal of Figure 1, Chapter 1, will allow the amplitude of the stronger-signal component in the limiter output to vary with limiter input signal amplitude in addition to the inescapable variation with a mentioned earlier, contributing to imperfect cancellation.

Bandpass Filter Difficulties. Ideally, all portions of a feedforward receiver ahead of the feedforward proper (front end and I. F. amplifier) should have a completely flat amplitude-vs-frequency characteristic over the entire range of frequency deviation of both stronger and weaker signals. Otherwise, the amplitudes of the two signals at the feedforward input will vary as their frequencies sweep over the passband, upsetting perfect stronger-signal cancellation over part of the modulation cycle. Achieving and maintaining such a flat I. F. characteristic while retaining steep skirts for adjacent-channel interference rejection requires considerable effort. When an I. F. stage is overloaded by too much input signal, its grid conducts and places a heavy, non-linear load on the tuned circuit connected to the grid, distorting the frequency response of the tuned circuit. A practical limiter has a relatively low, non-linear input impedance, which loads the tuned circuit to which it is connected, similarly distorting its frequency response.

It is also necessary, of course, to accurately match the amplitude and phase characteristics of the parallel limiter and amplifier channels over the entire signal bandwidth. In the simpler feedforward systems, this is easily done by combining the amplifier and limiter outputs before the limiter filter instead of after it. This makes no difference in the basic theory, of course, since the components which cancel each other are unaltered by the ideal filter, making combination before filtering equivalent to combination after filtering. More complex systems which may include frequency-sensitive elements in each channel require greater effort to achieve matching over the passband.

Ordinary Circuit Difficulties. Familiar design problems such as component aging, temperature variations, supply voltage variations, and shock and vibration can be rather troublesome in a feedforward receiver designed for small values of a, as will be explained quantitatively in the next section.

Degree of Precision to Which Requirements Must be Met. The specifications for the various components in a feedforward receiver have been discussed qualitatively from the standpoint of ideal requirements and the practical considerations which prevent the requirements from being met exactly. The next question is, exactly how closely must practical system components approximate the ideal? What exactly are the allowable tolerances on various parameters? It happens that the necessary precision varies rather widely with the input interference ratio a.

It is generally not too difficult to build a practical feedforward circuit which will capture the weaker co-channel signal at an a of about 0.5. As a increases toward 1, or decreases toward zero, weak-signal capture becomes increasingly difficult. The problems when $a \ll 0.5$ are different from those when $a > 0.5$. There is no real theoretical significance to the value $a = 0.5$; it is merely a convenient "bench mark".

Difficulties for $a > 0.5$. As a becomes larger than 0.5 and approaches 1, the shape of the passband of that part of the receiver ahead of the feedforward becomes increasingly important. If the passband is not flat over the modulation bandwidth, the stronger and weaker signals may exchange roles over a portion of the modulation cycle. An upper bound on the allowable departure from flatness is given by 100(1-$\underline{a}$) per cent, since such an error will make the two signal amplitudes instantaneously equal at one point in the modulation cycle.

Another effect is equally troublesome for $0.5 < \underline{a} < 1$: the requirements on the feedforward limiter become very stringent[3]. The maximum allowable limiter time constant approaches zero, and the requirements on limiting threshold and range of input amplitudes over which the limiter must remain saturated become more severe. Moreover, feedforward action is degraded because the maximum reduction in $\underline{a}$ available from a limiter declines from 6 db at $\underline{a} \leq 0.5$ to zero at $\underline{a} = 1$. Since practical limiters have a non-zero threshold, required limiter drive to maintain saturation quickly becomes unreasonably high. The net effect of these problems is that above some $\underline{a}_{max}$, $0.5 < \underline{a}_{max} < 1$, a practical limiter will fail to perform adequately in a feedforward system. It is usually possible to solve the problems mentioned adequately in the range $0.5 < \underline{a} < 0.8$ or 0.9. (See experimental results, Chapter 5.)

<u>Difficulties for $\underline{a} < 0.5$.</u> One fundamental problem arises at small values of $\underline{a}$ which is the source of a host of secondary difficulties: the maximum allowable variation in the value of K becomes very small at small $\underline{a}$, being approximately equal to 100($\underline{a}$/2) per cent for $\underline{a} < 0.5$. The outer limits on K as a function of $\underline{a}$ are plotted by Baghdady[6]; they are derived as follows. Obviously, if the

cancellation of the stronger-signal component in the limiter output by that in the amplifier output is not perfect (incorrect value of K), there will be a residual stronger-signal component in the feedforward output. If this residual component is equal to, or greater in amplitude than the residual weaker-signal component, capture of the weaker-signal component by a stronger-signal demodulator is impossible. The values of K at which the residual stronger-signal component is equal to the weaker-signal component are easily derived; these boundary values are given by

$$\text{Lower Bound} = \rho_{LW1} = \frac{A_o + A_{-1}}{1 + \underline{a}}$$

$$\text{Upper Bound} = \rho_{UW1} = \frac{A_o - A_{-1}}{1 - \underline{a}}$$

in which: A_o = normalized amplitude of stronger-signal component at limiter output

A_{-1} = normalized amplitude of weaker-signal component at limiter output

The values of A_o and A_{-1} as a function of $\underline{a}$ have been computed (1) and are given in Figure 1. Computation of ρ_{UW1} and ρ_{LW1} is straightforward with a knowledge of A_o and A_{-1}; these boundary values are plotted in Reference 6 as Figure 3. They are here replotted on a logarithmic scale with expanded abscissa to bring

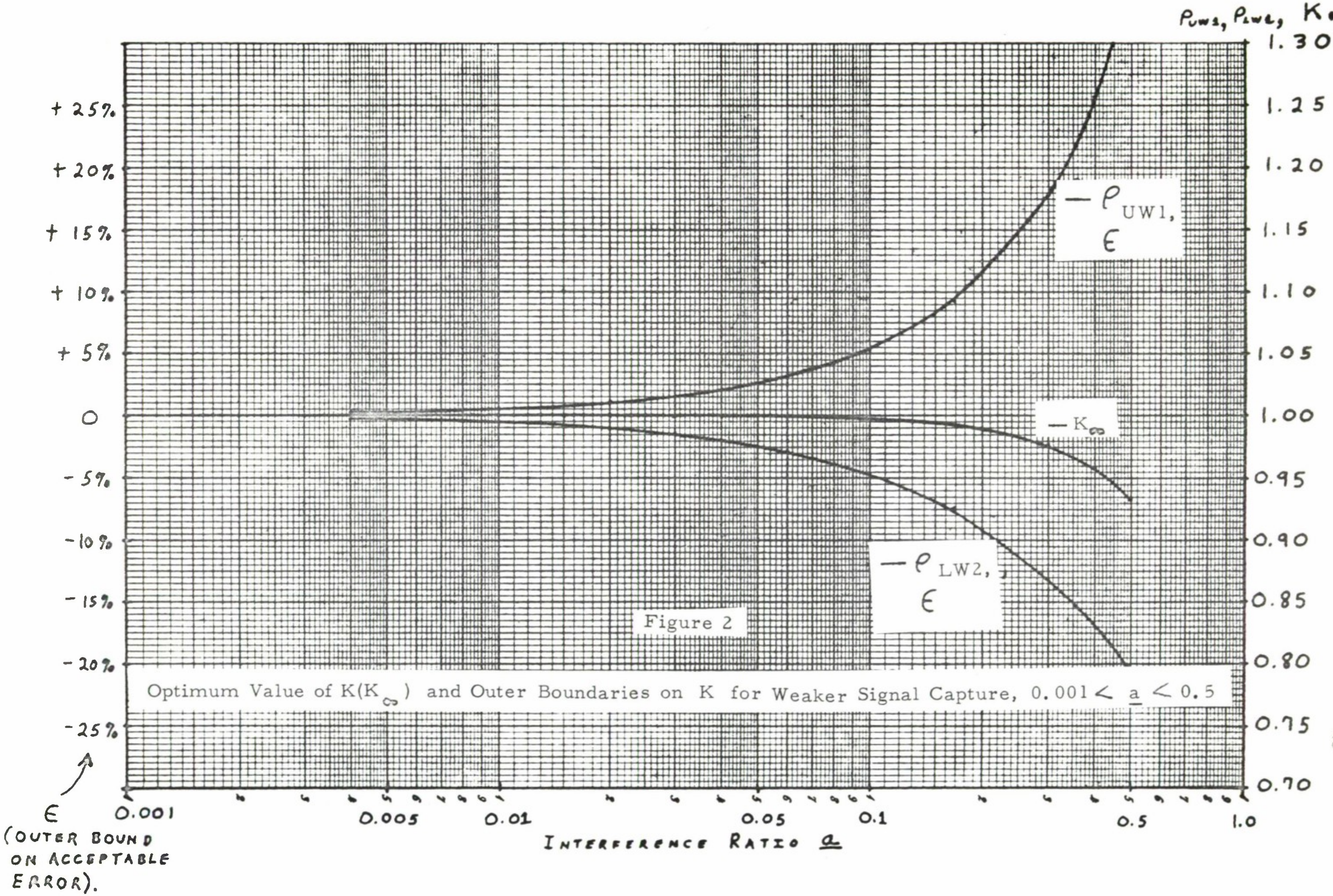


Figure 2

Optimum Value of $K(K_\infty)$ and Outer Boundaries on K for Weaker Signal Capture, $0.001 < a < 0.5$

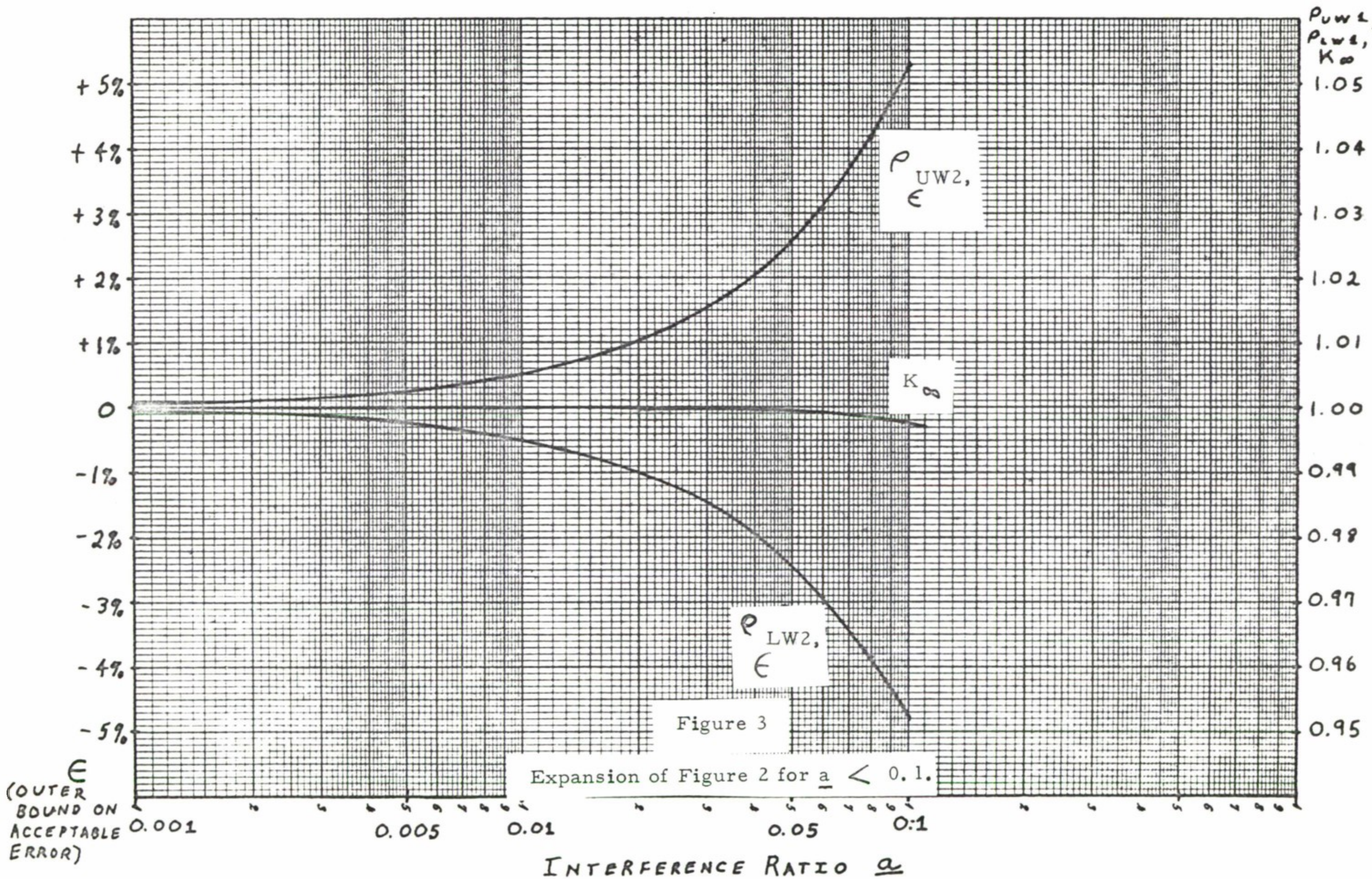


Figure 3

Expansion of Figure 2 for a < 0.1.

out their behavior for very small $\underline{a}$, along with $K_{\infty} = -A_o$, the value of K which gives perfect stronger-signal cancellation.

Figure 2 shows very clearly the drastic tightening of the outer boundaries on K as $\underline{a}$ decreases; Figure 3 is an expansion of the portion of Figure 2 below $\underline{a} = 0.1$, and shows that the allowable variation in K (denoted by ϵ) quickly falls from 5 per cent to less than 1 per cent as $\underline{a}$ decreases. This is a pretty stiff requirement in terms of practical equipment, since it means that limiter output level, feedforward amplifier gain, and feedforward amplifier input voltage must all be held to a precision of better than ϵ per cent over the entire receiver passband, despite short-term variations in input signal amplitude, component values, and supply voltages.

Neglecting the familiar perturbations due to such things as component drift and supply voltage changes, the requirements on K mean that the limiter characteristic must be flat to better than ϵ per cent over a range of $\frac{1 + \underline{a}}{1 - \underline{a}} : 1$ in input voltage. Fortunately, a smaller portion of the limiter characteristic is involved at smaller $\underline{a}$. The requirements also mean that all portions of the receiver ahead of the feedforward must have a frequency characteristic that is flat within ϵ per cent over the entire range of frequency deviation of the input signals, as must the bandpass filter following the feedforward limiter. This requirement would not be nearly so difficult were it not also necessary for the frequency characteristic of the front end and I. F. to slope off sharply at the band edges to reject adjacent-channel interference and for the feedforward limiter filter to cut off sharply in order to reject as many of the additional components introduced by limiting as possible. Thus, as $\underline{a}$ decreases, the required bandpass filter shapes required for reasonable performance approach the ideal rectangular shape very quickly.

From an engineering point of view, the precision of better than 1 per cent required to capture weaker signals below $\underline{a} = 0.02$ (see Figure 3) is very difficult to achieve. Thus, a feedforward for the capture of weaker signals below $\underline{a} = 0.02$, though conceptually very simple, would be anything but simple to design and construct, and would be rather unattractive from a practical or economic standpoint.

(3) Feedforward Amplifier Linearity

Linearity of the feedforward amplifier is usually not too difficult to obtain with reasonable care in design. The amplifier must be linear over a range of $\frac{1 + \underline{a}}{1 - \underline{a}}$ to 1 in input signal amplitude when no pre-limiter is used. Since its gain must be controllable, the amplifier must maintain linearity for all gain control settings. It is also necessary to insure that the largest receiver input signal to be encountered will not overload the amplifier.

A Minor Practical Problem. In practice, the amplitude of the residual weaker-signal component in the feedforward output is usually too low to adequately drive the first limiter in the demodulator, making it necessary to provide a single-stage amplifier after the simple feedforward of Figure 5, Chapter 1. For the feedforward to work over a wide range of <u>a</u>, this amplifier must have a reasonably wide dynamic range, since residual weaker-signal output varies with <u>a</u>. This point was missed in earlier feedforward designs[7, 8], and no amplifier was included; this reduced system capabilities considerably.

CHAPTER 3

RELATIVE MERITS OF VARIOUS PRACTICAL FEEDFORWARD CIRCUITS

Summary of Requirements

The construction of a high-performance feedforward requires an excellent narrow-band limiter, a linear amplifier of readily controllable gain, bandpass filters which are accurately flat over the modulation bandwidth, and a circuit arrangement which provides an accurate 180° phase difference at the limiter and amplifier outputs. The quantitative requirements on these various components were discussed in Chapter 2.

Possible Basic Circuit Configurations

The Transformer-Input Feedforward

Figure 1 is a basic diagram of one possible feedforward circuit. The outputs of the limiter and linear amplifier are combined in phase by simply adding their plate currents in a common plate load. The 180° phase difference is achieved by the use of a tuned transformer with a center-tapped secondary, its primary being fed from the plate of the preceding stage (the last I. F. stage if no pre-limiter is used).

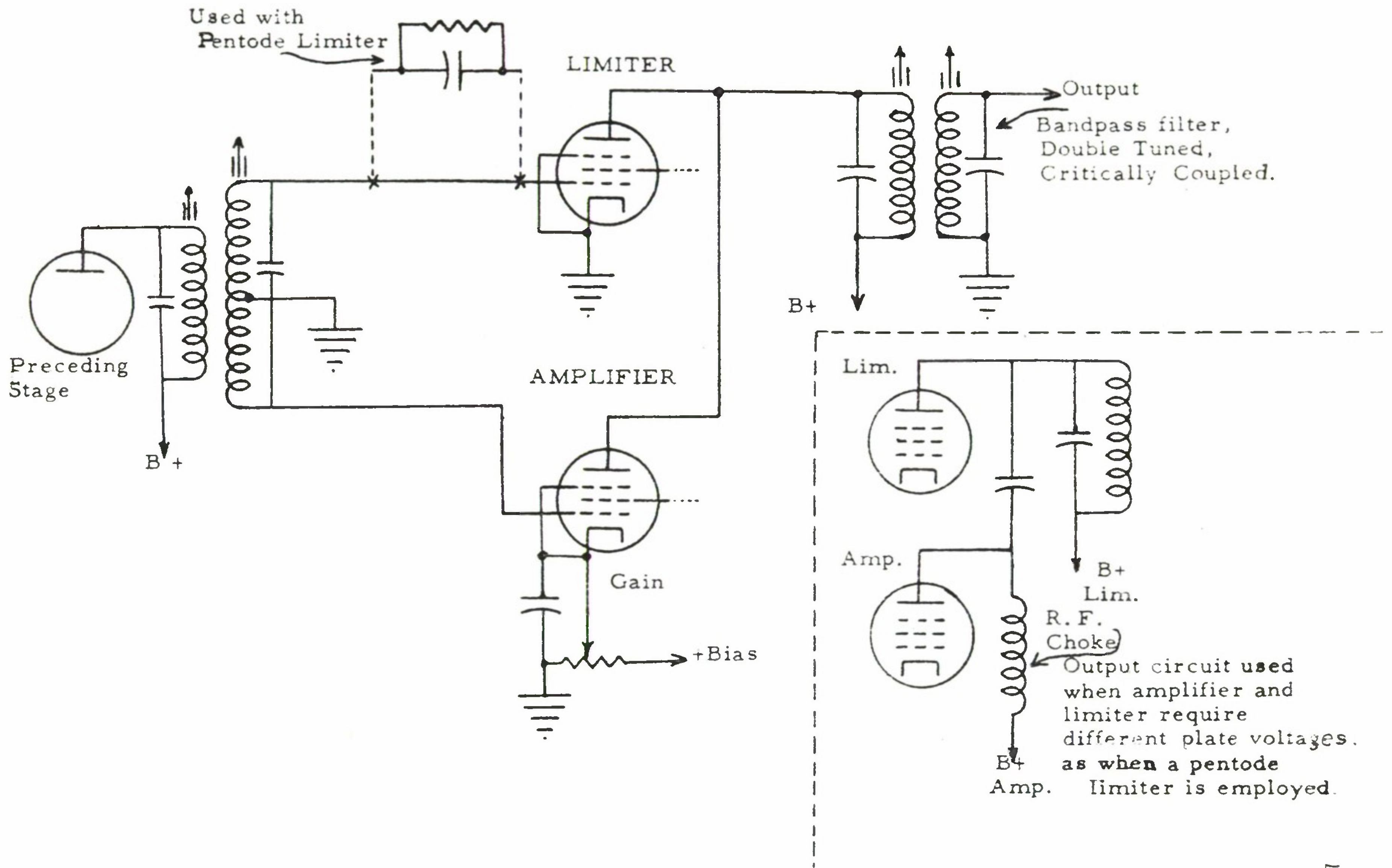


Figure 1: Basic Transformer-Input Feedforward Circuit

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The inputs to the limiter and amplifier are connected to opposite ends of the balanced secondary winding, which are close to 180° apart over the passband of the tuned transformer.

The limiter and amplifier outputs are combined ahead of the limiter filter, as explained in Chapter 2. The value of K is controlled by the bias potentiometer in the cathode of the variable-μ amplifier tube.

One primary advantage of this circuit is its simplicity, there being only two tubes and four tuned-circuit adjustments in the feedforward proper. It is adaptable to almost any frequency at which the tubes will function well and at which a suitable input transformer can be built.

The main problem of the circuit is loading of the tuned input transformer by the limiter. A limiter input usually presents a low impedance, non-linear load which can distort the passband shape of the tuned transformer. The non-linear load on the last I. F. stage also means that the input signal to the feedforward amplifier will be partially limited, which is undesirable. The bad effects of non-linear loading may be eliminated by sufficiently lowering the impedance level of the transformer, but an engineering compromise is necessary, since lower impedance at this point means less voltage to drive the limiter for a fixed g_m in the last I. F. stage. Use of a broadband untuned input transformer might alleviate the problem somewhat; recent advances in ferrite core materials and winding techniques have made construction of such transformers quite feasible for frequencies up to 50 mc.

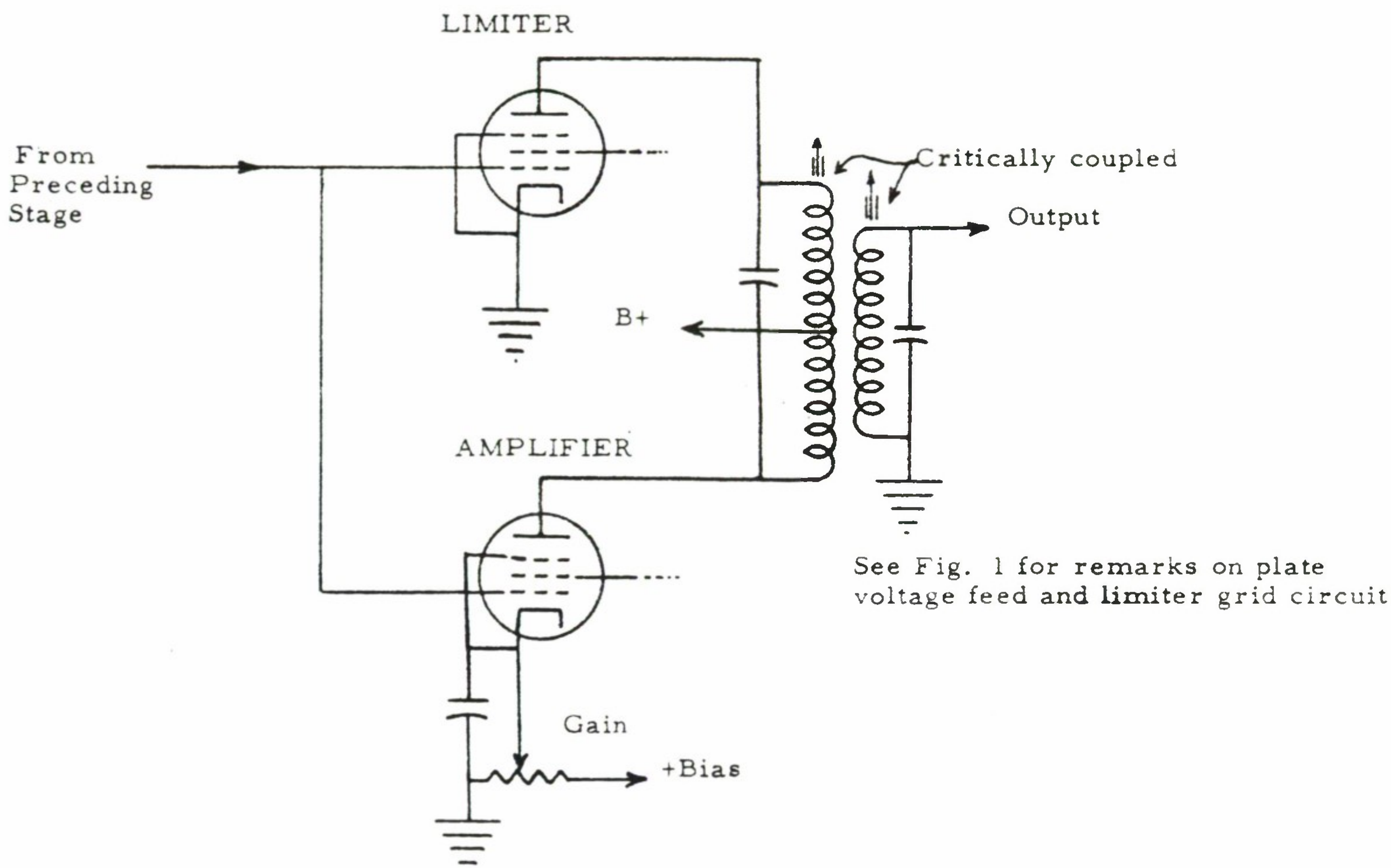


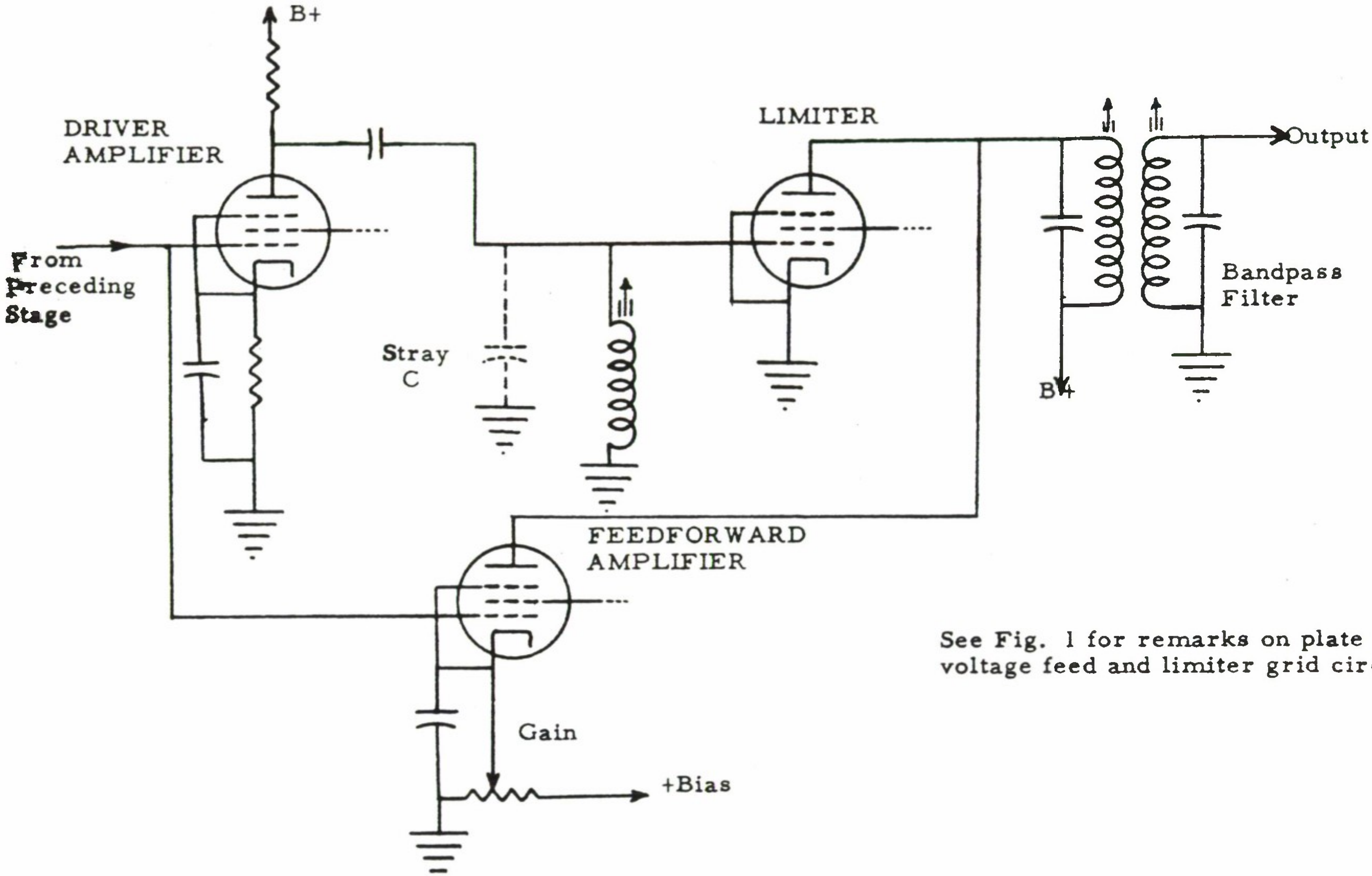
Figure 2: Basic Transformer-Output Feedforward Circuit

The Transformer-Output Feedforward

Figure 2 indicates another possible way in which a center-tapped transformer may be used to obtain correct phase relationships in a feedforward circuit. The limiter and amplifier inputs are fed in phase, their outputs being combined subtractively in the transformer. This circuit arrangement preserves the simplicity of the transformer-input feedforward while avoiding the problem of limiter loading on the phase-inverting transformer. If used in its simplest form, i.e., if fed through a double-tuned circuit from the plate of the last high-gain I.F. stage, loading of the tuned circuit by the limiter will, of course, be a problem. The addition of a driver stage with a broadly tuned, low-impedance output circuit sacrifices the inherent simplicity of the circuit to solve the loading problem.

The Driver-Limiter Feedforward

The feedforward circuit of Figure 3 avoids the problems of limiter loading and design of a center-tapped tuned transformer. The limiter is driven by a linear amplifier with a very low Q single-tuned plate circuit. The necessary 180° phase difference between channels is obtained by the use of two stages in the limiter channel and one in the amplifier. The tuned circuit between the driver amplifier and the limiter must have a low enough Q to have negligible phase shift over the passband of interest, and must have a low enough impedance so that the non-linear load represented by the limiter input will not affect its characteristics. The two amplifier grids connected to the last tuned circuit in the I.F. amplifier have a negligible loading effect.



See Fig. 1 for remarks on plate voltage feed and limiter grid circuit.

Figure 3: Basic Driver-Limiter Feedforward Circuit

The driver-limiter feedforward has several controls and complications not shared by the two simpler circuits described earlier such as the gain control on the driver amplifier and the tuning of the driver amplifier plate circuit. However, these extra controls provide advantages as well as complications. The gain of the driver amplifier may be adjusted to insure that the limiter remains saturated at all times and that the input signal amplitude variations occupy the flattest and "best" portion of the limiter characteristic at small $\underline{a}$. The interstage tuning control can be varied slightly to adjust the phase difference in the channel outputs to exactly 180°.

The Grounded-Grid-Amplifier Feedforward

Figure 4 is a diagram of the circuit used in two previous investigations of feedforward.[7, 8] The amplifier and limiter are connected in phase at both input and output; the necessary phase difference in the two channels is achieved by using a grounded-grid amplifier. A cathode follower is necessary to provide a low-impedance source to match the low input impedance of the grounded-grid amplifier.

The circuit appears reasonably attractive at first glance, but a second look reveals some serious fundamental difficulties, most of them connected with the cathode follower. The circuit uses a minimum of three tubes but offers few if any compensating advantages over the simpler arrangements using two tubes. The cathode follower is usually thought of as extremely stable, linear, and trouble-free, but these generalizations no longer hold when it is used with tuned circuits and at

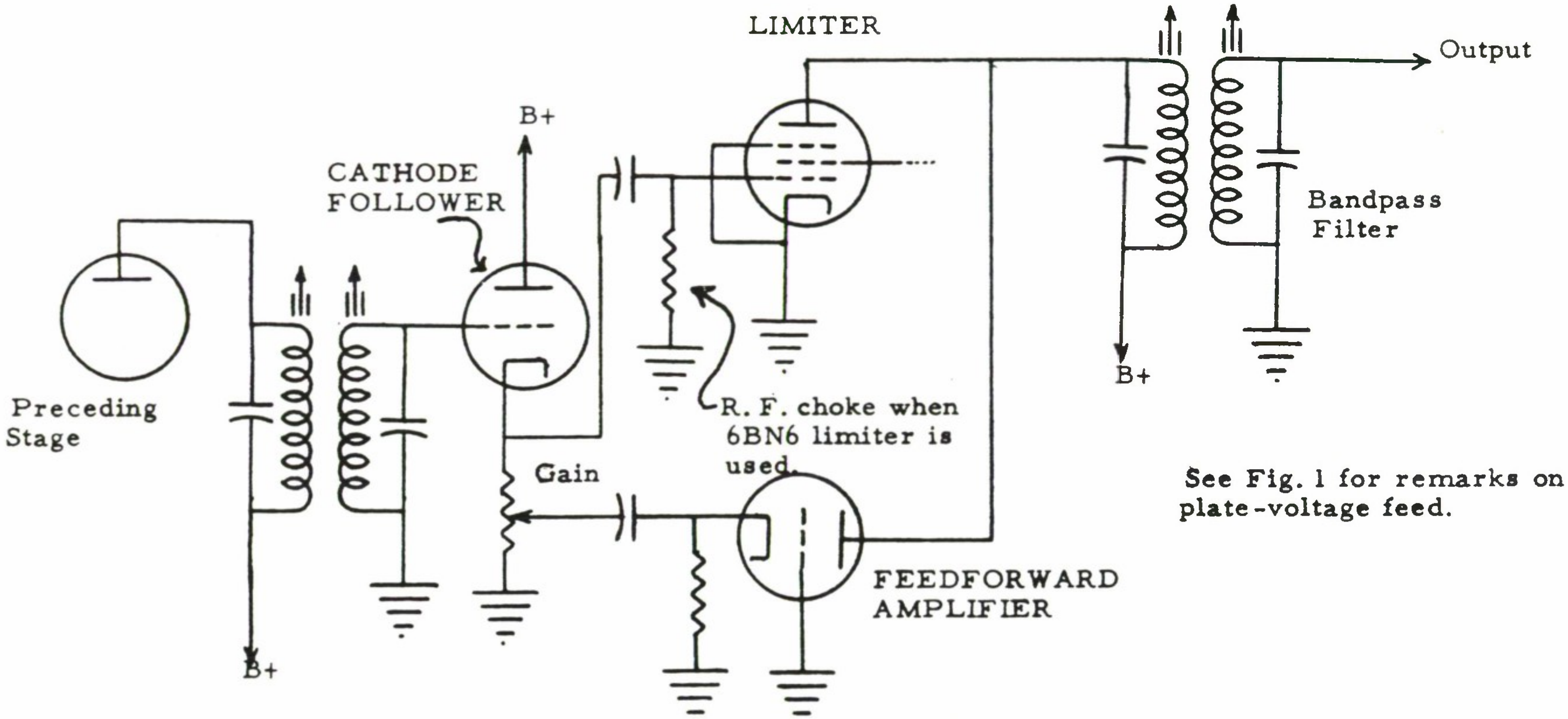


Figure 4: Basic Grounded-Grid Amplifier Feedforward Circuit

frequencies in the megacycle region, such as are commonly used as intermediate frequencies in FM receivers. Special precautions may be necessary to prevent oscillation when a tuned circuit is connected to a cathode-follower grid; the stray capacitances combine to form a Colpitts oscillator circuit, as shown in Figure 5. Also, the stray capacitance from cathode to ground of the cathode follower may be quite large, since it consists of cathode-heater capacitance plus plate-cathode capacitance plus the input capacitance of the load, which in the present case consists of heater-cathode and grid-cathode capacitance of the tube in the grounded grid stage. The total shunt capacitance may amount to 50 mmf or more; unless the impedance from cathode to ground is kept extremely small, the shunt capacitance can easily slow the rise time of the cathode circuit to such an extent that the cathode-follower grid will rise quickly to the grid conduction point or fall below the cutoff point before the cathode voltage can change correspondingly. The result is non-linearity and clipping. If the cathode impedance is made low enough to prevent clipping, it becomes difficult to provide enough voltage at the cathode follower output to drive the limiter adequately without resorting to tubes of extremely high g_m for the cathode follower, which in turn aggravates the problem of oscillation.

In the versions of this circuit which were actually constructed,[7, 8] a potentiometer in the cathode follower output was used to control the feedforward amplifier gain. This is a rather dubious method of gain control for frequencies in the megacycle region, but there is no obvious alternative.

A cathode follower with tuned-circuit input becomes a Colpitts-type oscillator at a sufficiently high frequency. Resistor of 50-1000 ohms at "X" will often help suppress oscillation.

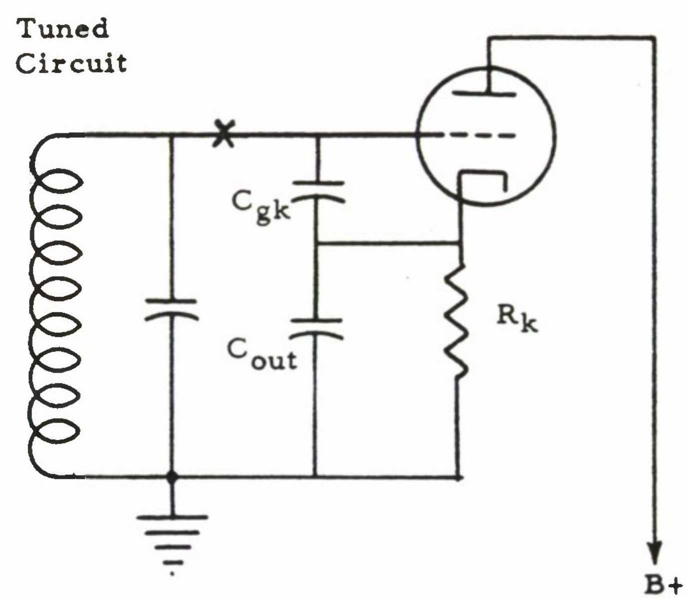


Figure 5: Oscillator Circuit Formed by Cathode Follower with Tuned Input Circuit.

The problems of this circuit would be somewhat less formidable at low I. F. frequencies where the cathode follower circuit would be less troublesome. A step-down transformer may be used to match the low input impedance of the grounded-grid amplifier; however, this would require very high primary voltages to provide enough drive at the secondary to drive the limiter adequately. It is very difficult to see any advantage to this circuit over the others mentioned in this chapter at normal FM I. F. frequencies of several megacycles.

Use of a Split-Load Phase Inverter

The 180° phase difference necessary in a feedforward circuit might be conceivably obtained from a split-load phase inverter of the type popular in audio amplifiers, in which outputs are taken from both plate and cathode of a single tube. However, this approach would be useful only at rather low I. F.'s since the phase inverter circuit has the same troubles as a cathode follower plus a few of its own when used at high frequencies.

CHAPTER 4

DESCRIPTION OF EXPERIMENTAL EQUIPMENT

Laboratory Receivers

Figure 1 is a block diagram of the type of laboratory-model receiver used in the experimental measurements. Since all measurements were made with signal generators, an R. F. stage and mixer were unnecessary and were not included, signals being fed in at the intermediate frequency (10.7 mc). The feedforward circuit was inserted between a more or less conventional I. F. amplifier and a high-capture-ratio demodulator. The entire system was designed around the standards used in F. M. broadcasting: 10.7 mc I. F. and $\pm$ 75 kc maximum peak deviation.

In order to compare the performance of different types of feedforward circuits, experimental models were built of the three most promising circuits of Chapter 3: the transformer-input circuit, the transformer-output circuit, and the driver-limiter circuit. Each was tested separately; the same demodulator and I. F. amplifier were used for all tests. The transformer-input feedforward was built first and thus included a pre-limiter. The driver-limiter feedforward, constructed next, used a pre-limiter at first and was later modified to eliminate it. The transformer-output feedforward was built initially without the pre-limiter.

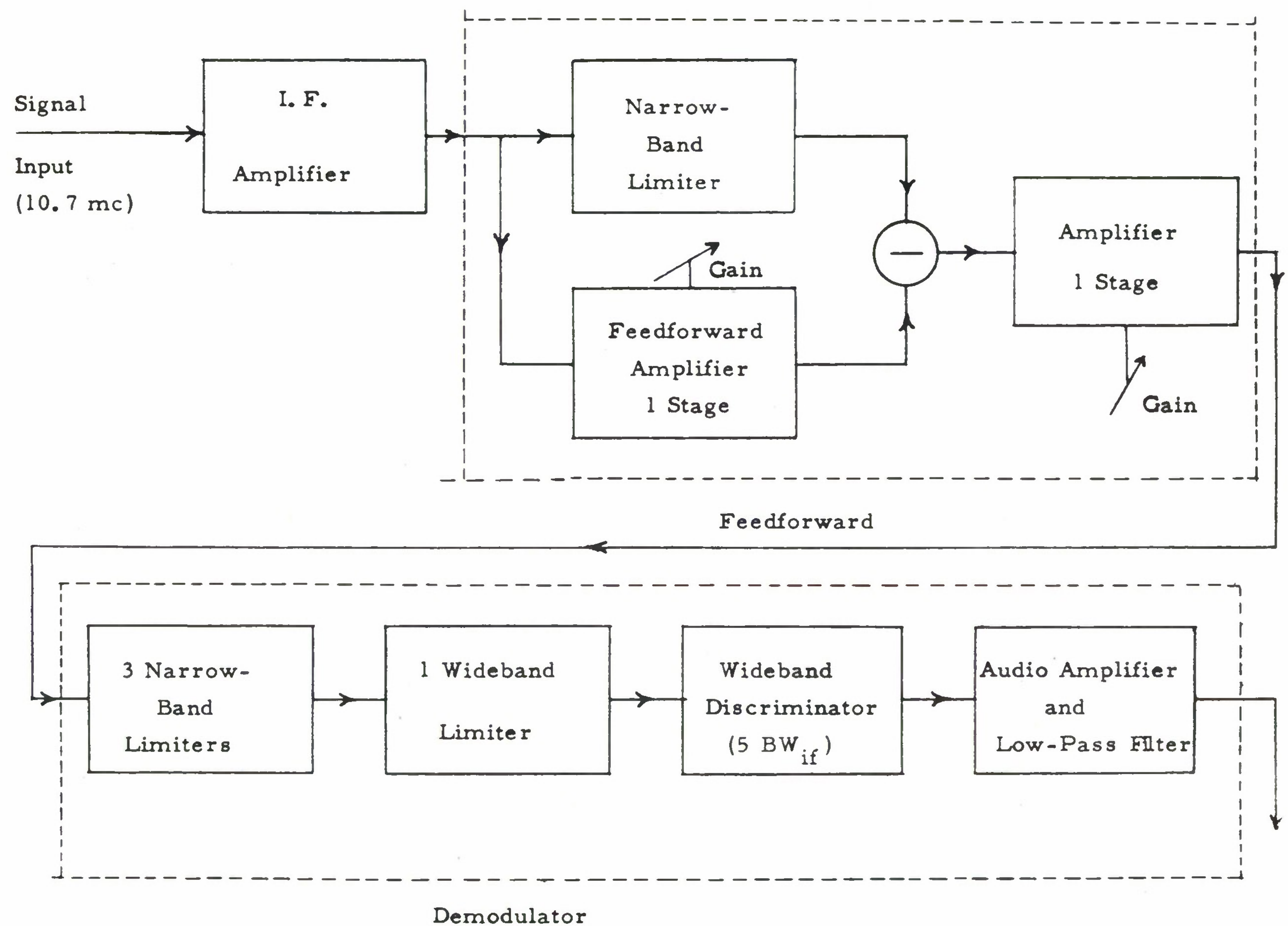


Figure 1
Block Diagram of Laboratory Model Receiver

From these basic component circuits, three different "models" of the feedforward receiver of Figure 1 could be assembled. The various receiver components will be described separately.

The I. F. Amplifier

Figure 2 is a schematic of the I. F. amplifier used in the experimental receivers. Most of its design features are strictly conventional. The resistive input network is designed to properly terminate the two signal generator cables and to provide isolation between generators. Multiple bypass capacitors connected to different ground lugs are used at several points; this arrangement greatly improved the stability of the amplifier. Shielded power cables plus the isolation chokes shown in the power leads were necessary to provide isolation between stages and between the amplifier and other units sharing the common power supply.

Commercial 10.7 mc I. F. transformers of the type commonly employed in F. M. broadcast receivers were used in the amplifier, for several reasons. They are compact, inexpensive, readily available, and well shielded, and their use greatly simplifies the construction of equipment using tuned circuits. Savings in construction time were quite valuable, since a considerable amount of hardware had to be built in the limited time available for the investigation.

Unfortunately, the degree of precision necessary in the I. F. amplifier response in a feedforward receiver (see Chapter 2) was not fully appreciated at the beginning of the investigation. Therefore, the

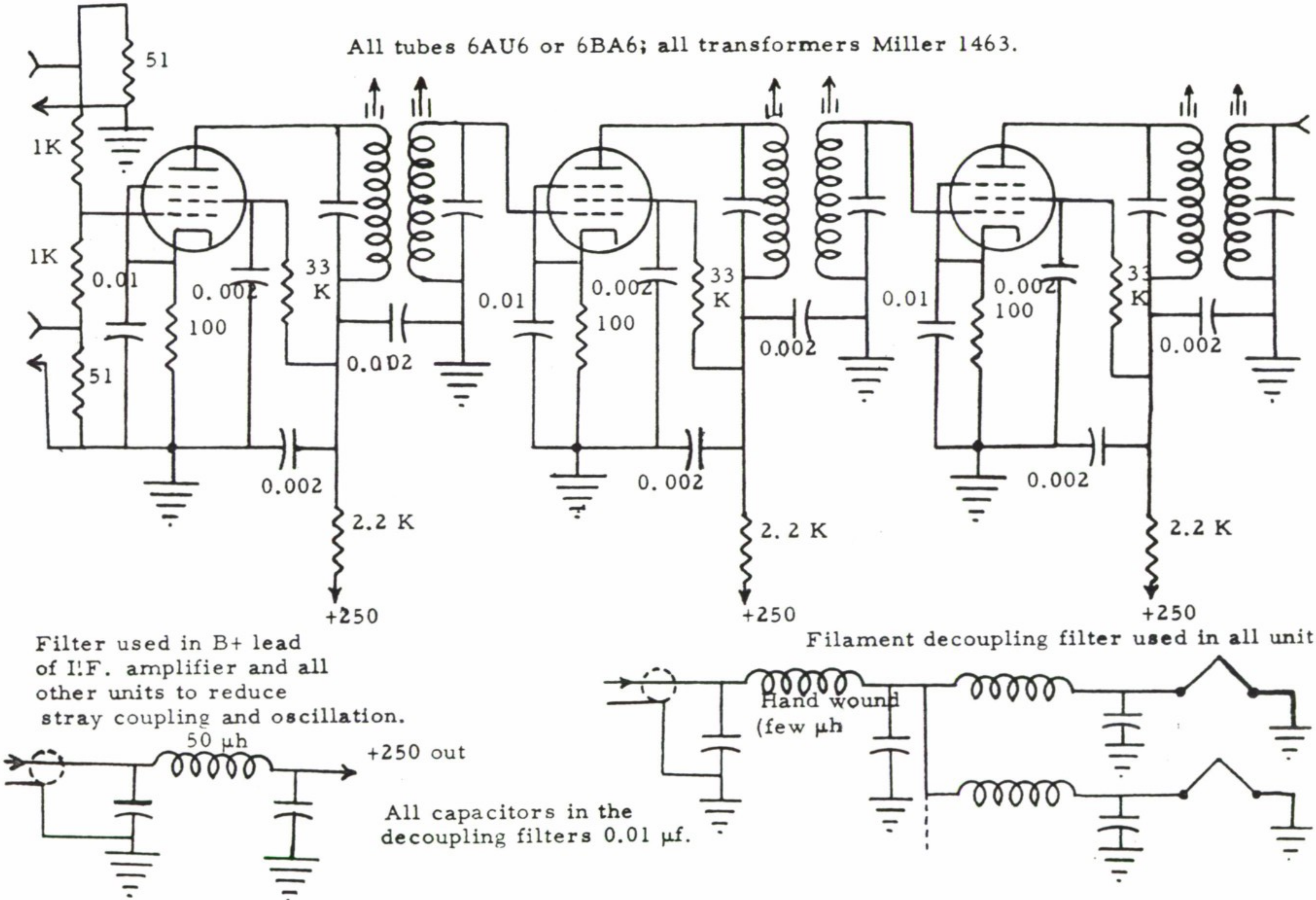
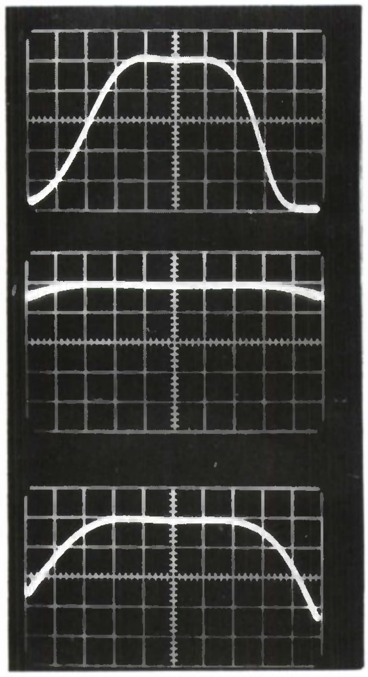


Figure 2: Schematic of the 3-Stage I. F. Amplifier



40 kc per division

15 kc per division

25 kc per division

The I. F. amplifier frequency-response curve shown above was measured at the same time as the capture plot of Figure 19, Chapter 5.

The alignment adjustments are the same for all three pictures; only the frequency-scale calibration (horizontal scale) is different, as indicated. The vertical scale is linearly calibrated in relative amplitude.

Figure 3

Frequency-Response Curves of I. F. Amplifier worst disadvantages of the commercial transformers (very poor stability, relatively high impedance, rounded frequency characteristic) did not appear too serious to begin with. It later became apparent that the tuning adjustments of the transformers drifted with time, temperature, and vibration to a degree which was quite tolerable in a broadcast receiver but inacceptable in a precisely adjusted feedforward receiver. It was therefore constantly necessary to touch up the alignment of the experimental receiver to obtain best performance. The commercial transformers were improved considerably by opening their cans and sliding the coils closer together to increase the coefficient of coupling and flatten their frequency response. The first transformer used in the I. F. amplifier was overcoupled, the second undercoupled slightly, and the third loaded somewhat and critically coupled to obtain the flat-topped over-all response of Figure 3.

It was discovered that the use of 6BA6 tubes in the amplifier resulted in slightly less gain than 6AU6's but a wider dynamic range, i.e., the response curve preserved its shape over a wider range of input voltages - an important advantage.

The Demodulator

Figure 4 is a schematic of the receiver demodulator. It employs four pentode-type limiters; commercial I. F. transformers identical to those in the I. F. amplifier were used as interstage narrow-band filters. The discriminator is basically the conventional Foster-Seeley type. The audio section includes a cathode follower to isolate

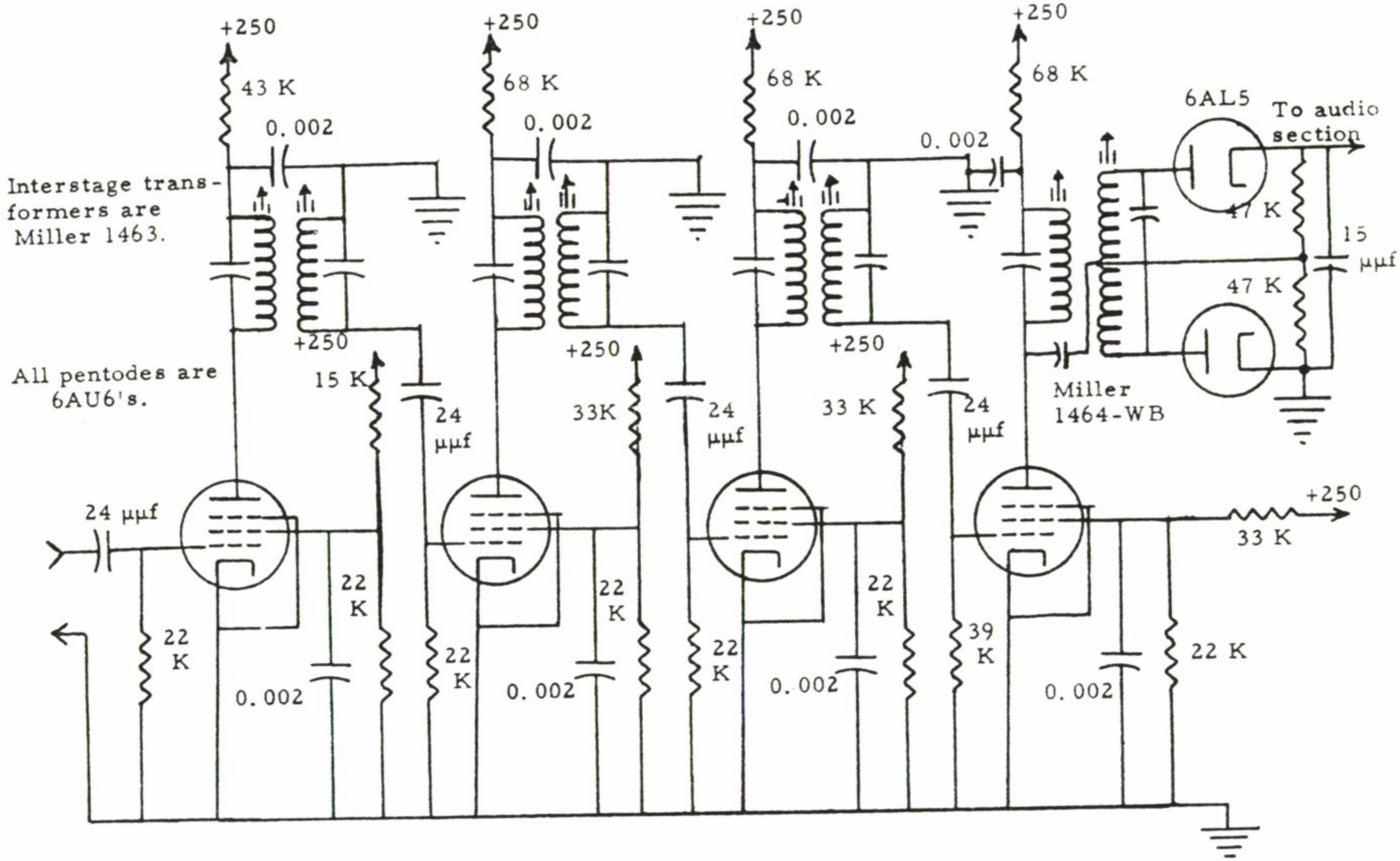


Figure 4: Schematic of the High-Performance Demodulator with Later Model Audio Section (Part 1 of 2 parts)

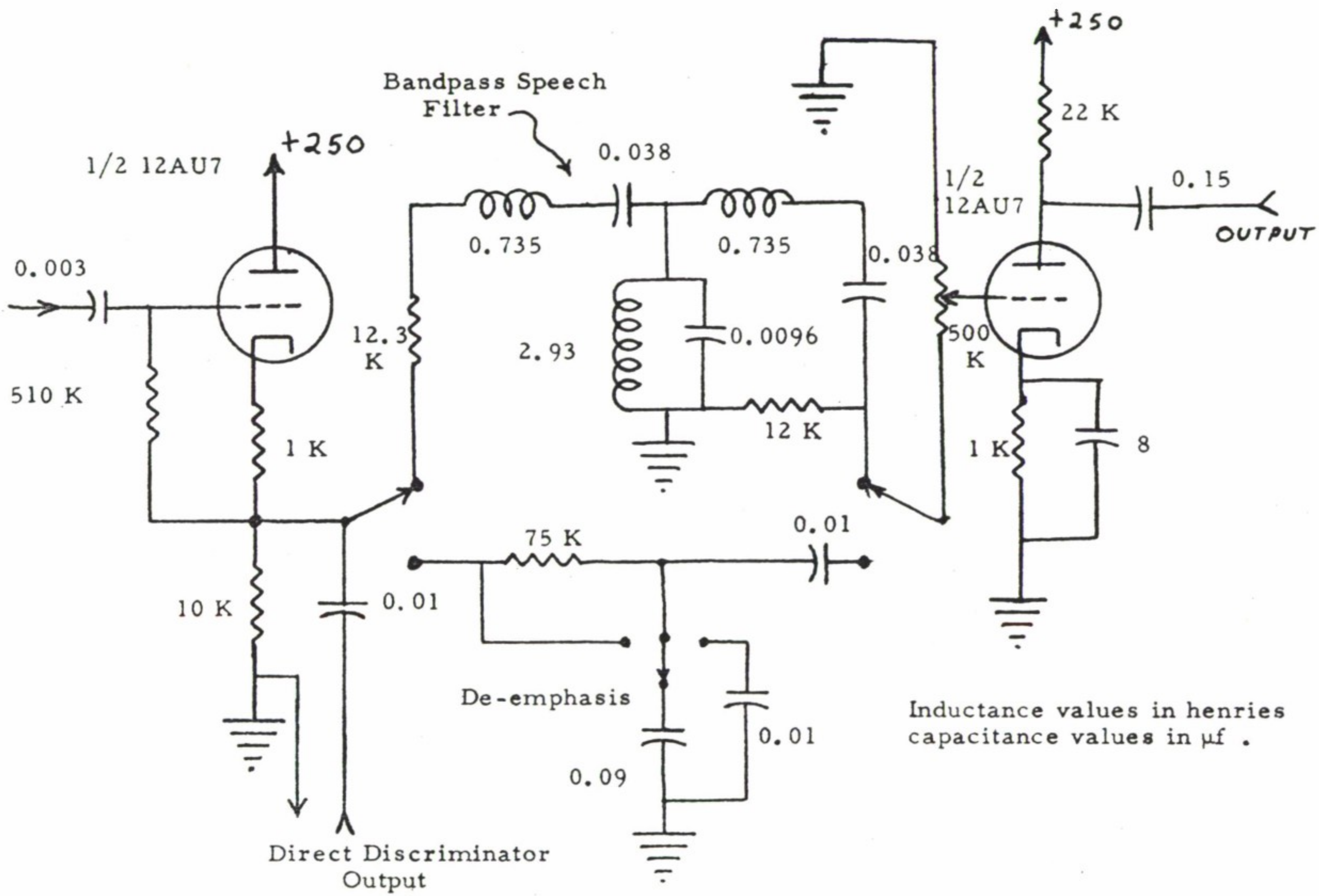


Figure 4 (continued)

The Audio Section

the discriminator output circuit from following stages and from test equipment used to observe the discriminator output directly. This arrangement keeps the discriminator output capacitance low, insuring the low discriminator time constant necessary for high capture ratio.[3] The audio section also includes one conventional voltage amplifier stage and provision for switching in either a bandpass speech filter (see Figure 5) or varying amounts of R-C de-emphasis. The earlier model audio section shown in Figure 6 included provision for R-C de-emphasis plus low-pass filtering (Figure 7 and 8) and was used for initial measurements before the design of Figure 4 was evolved as a much better compromise for the reception of speech-modulated signals, as explained in Chapter 5.

Figures 9, 10, 11, and 12 show the dramatic improvement in the performance of a practical demodulator which can be obtained by applying the theoretical principles outlined in References 1 through 4. Figure 9 shows the capture plot of the demodulator as originally built, with reasonably low limiter time constants. A commercial broadcast-type discriminator transformer with 320 kc peak separation was used in the manufacturer's recommended circuit. Figure 10 was obtained by lowering the discriminator time constant to 3 μsec and reducing the limiter time constants somewhat. Figure 11 shows the improvement obtained by substituting a commercial wideband discriminator transformer (900 kc between peaks) which is sold for high-fidelity tuners; no other changes were made from the conditions of Figure 10. The characteristic of Figure 12 was obtained by merely lowering the discriminator time constant to 1.4 μsec.

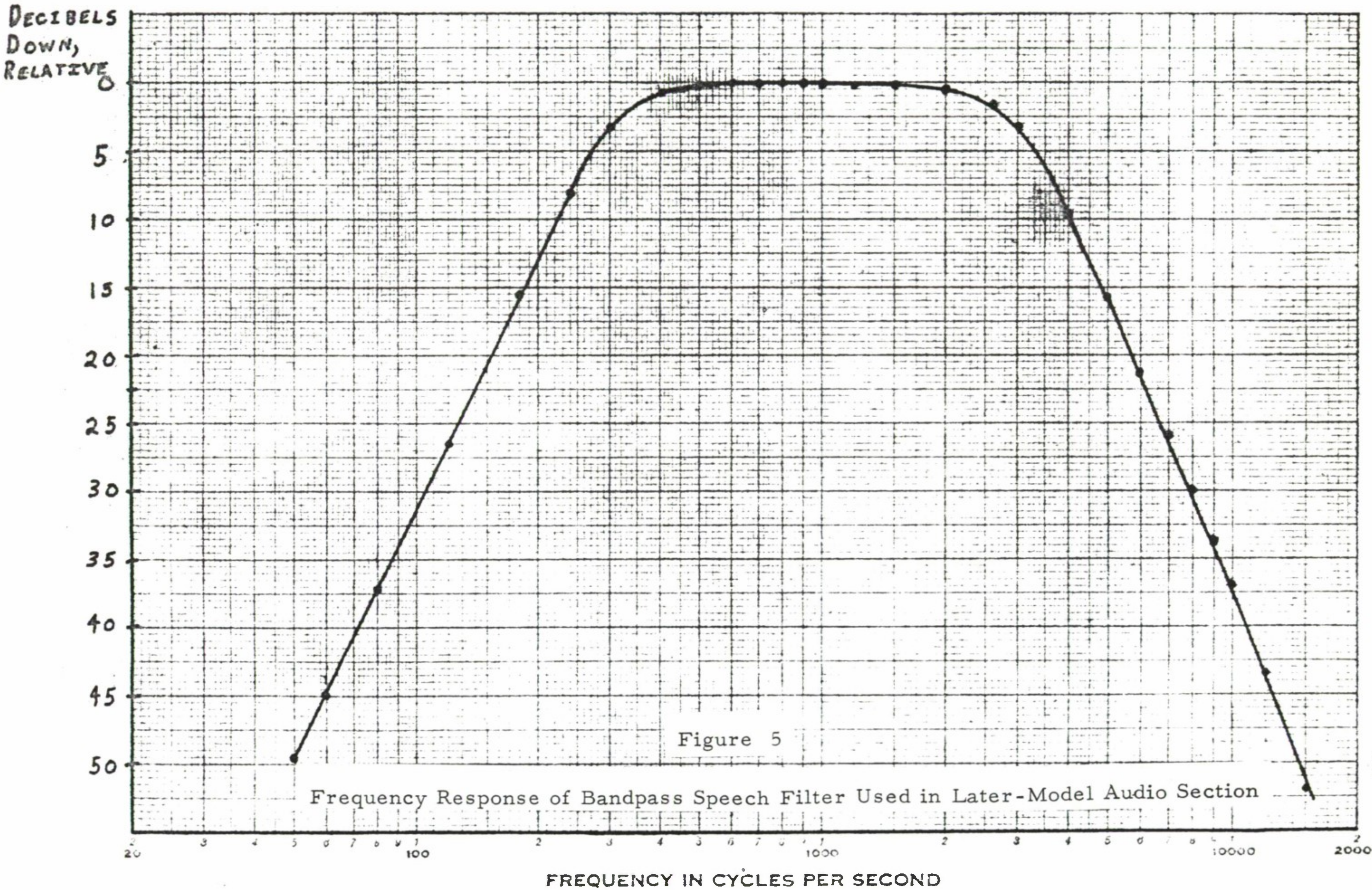


Figure 5

Frequency Response of Bandpass Speech Filter Used in Later-Model Audio Section

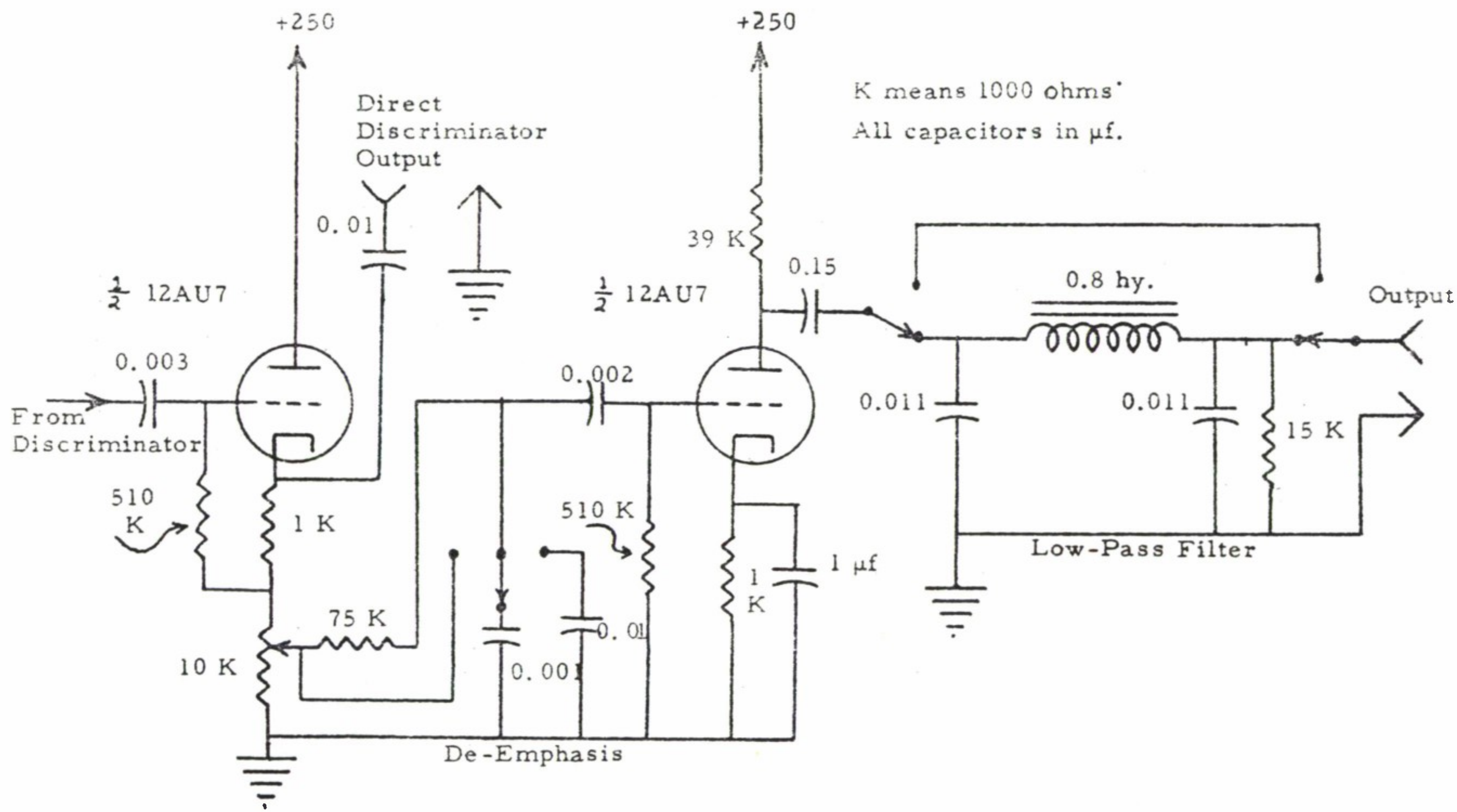


Figure 6: Early-Model Audio Section used in Demodulator

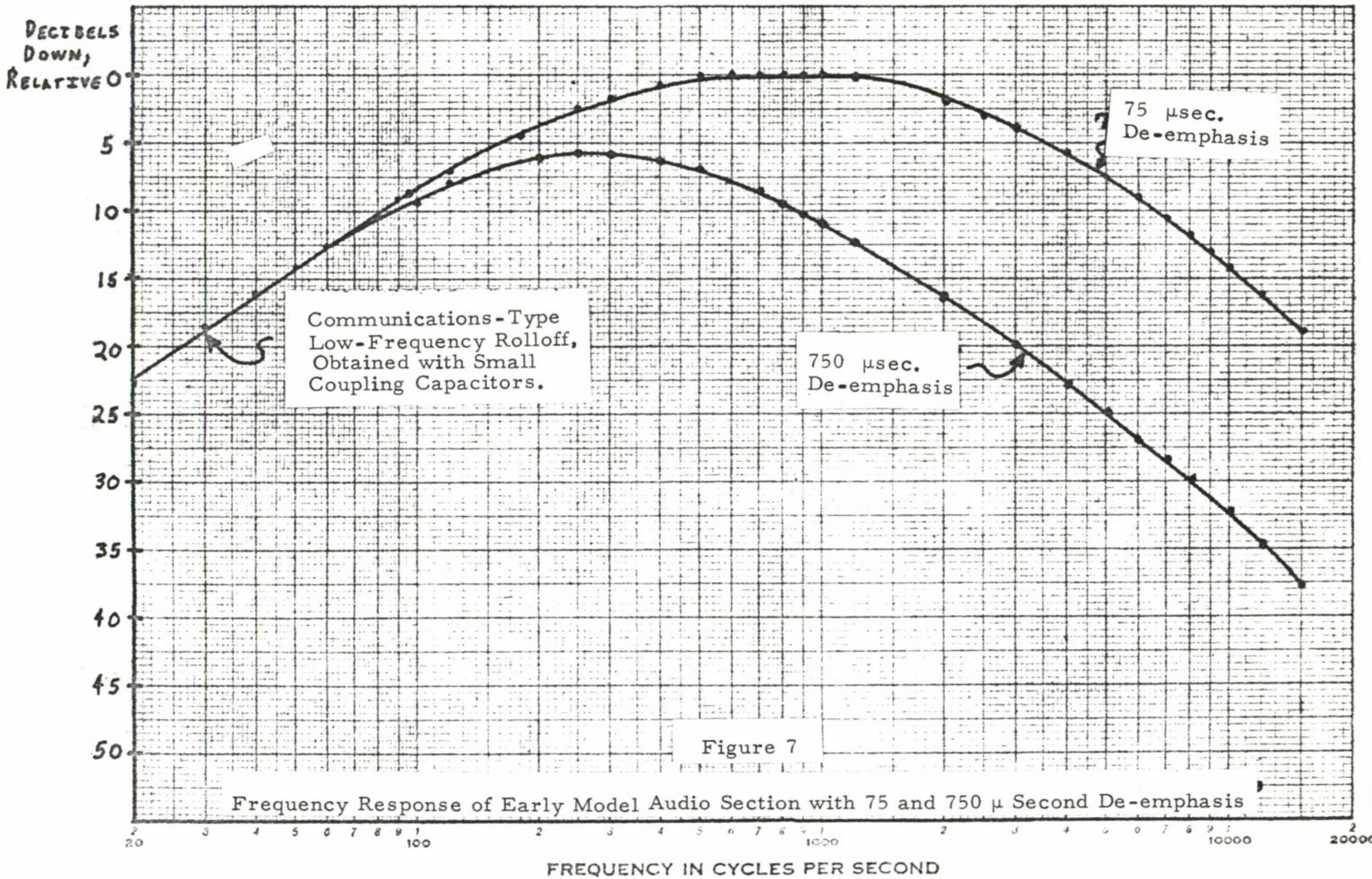


Figure 7

Frequency Response of Early Model Audio Section with 75 and 750 µ Second De-emphasis

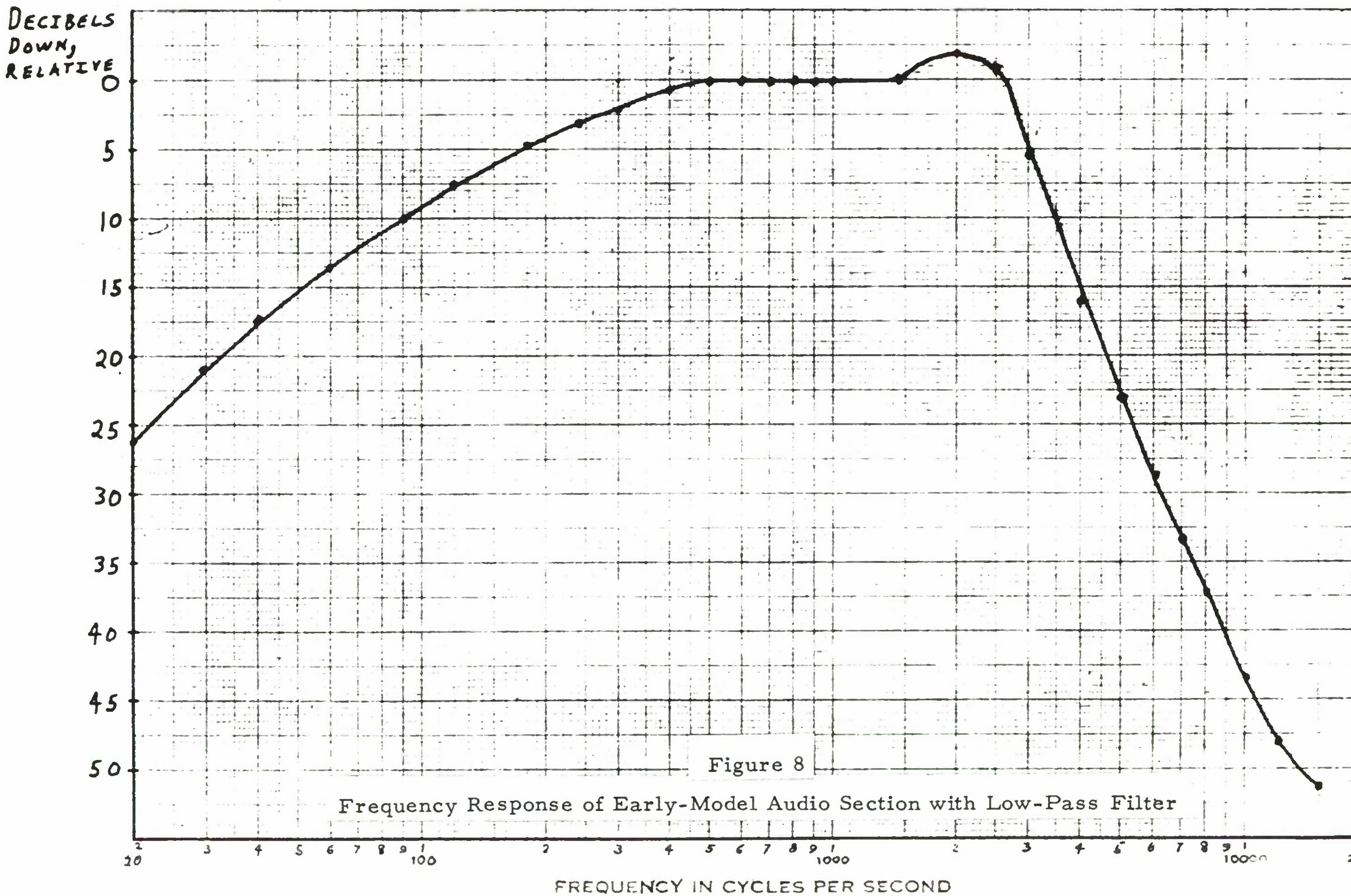


Figure 8

Frequency Response of Early-Model Audio Section with Low-Pass Filter

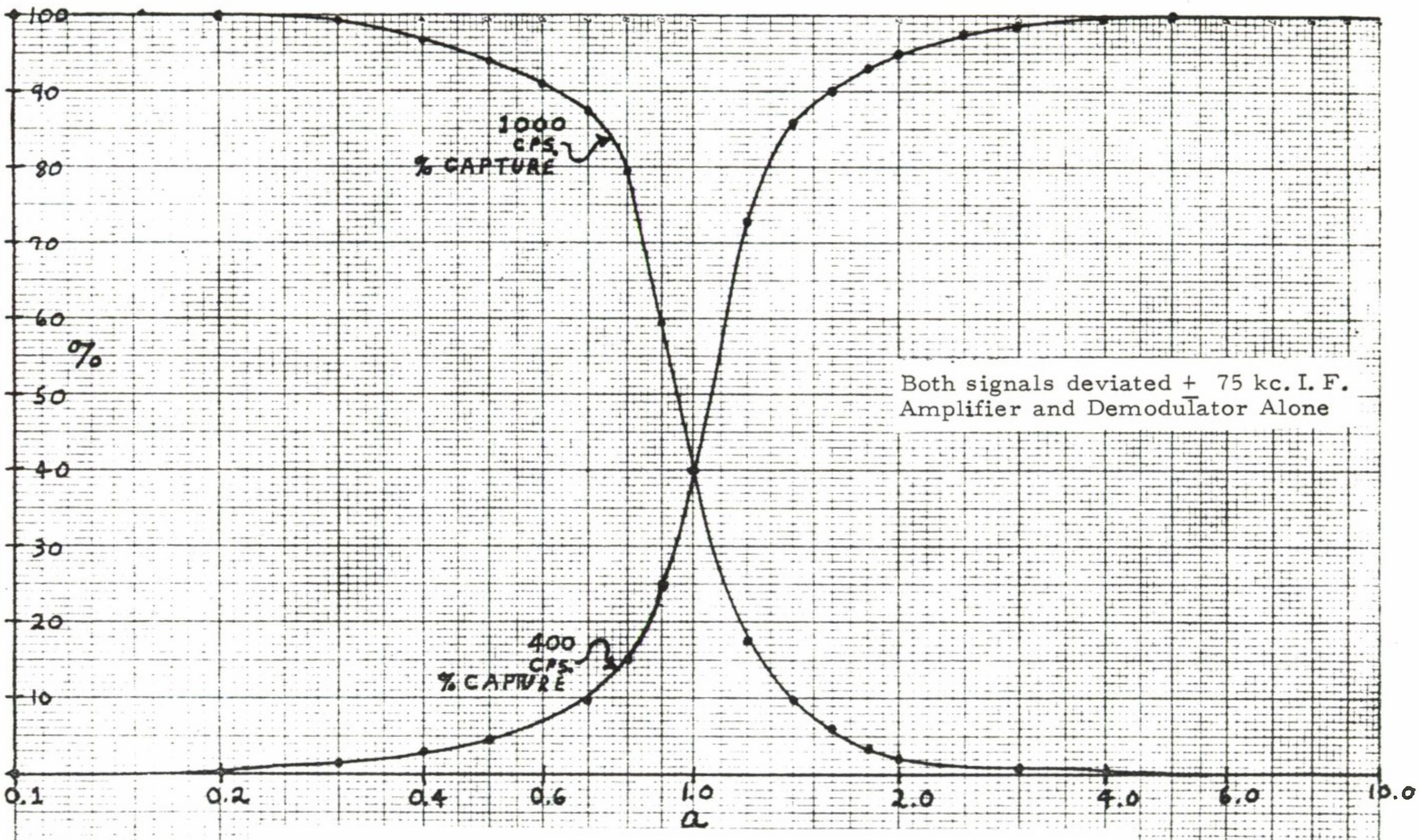


Figure 9: Capture Plot of Demodulator as Originally Constructed with 320 kc. Discriminator (Miller No. 1464) Used in Recommended Circuit

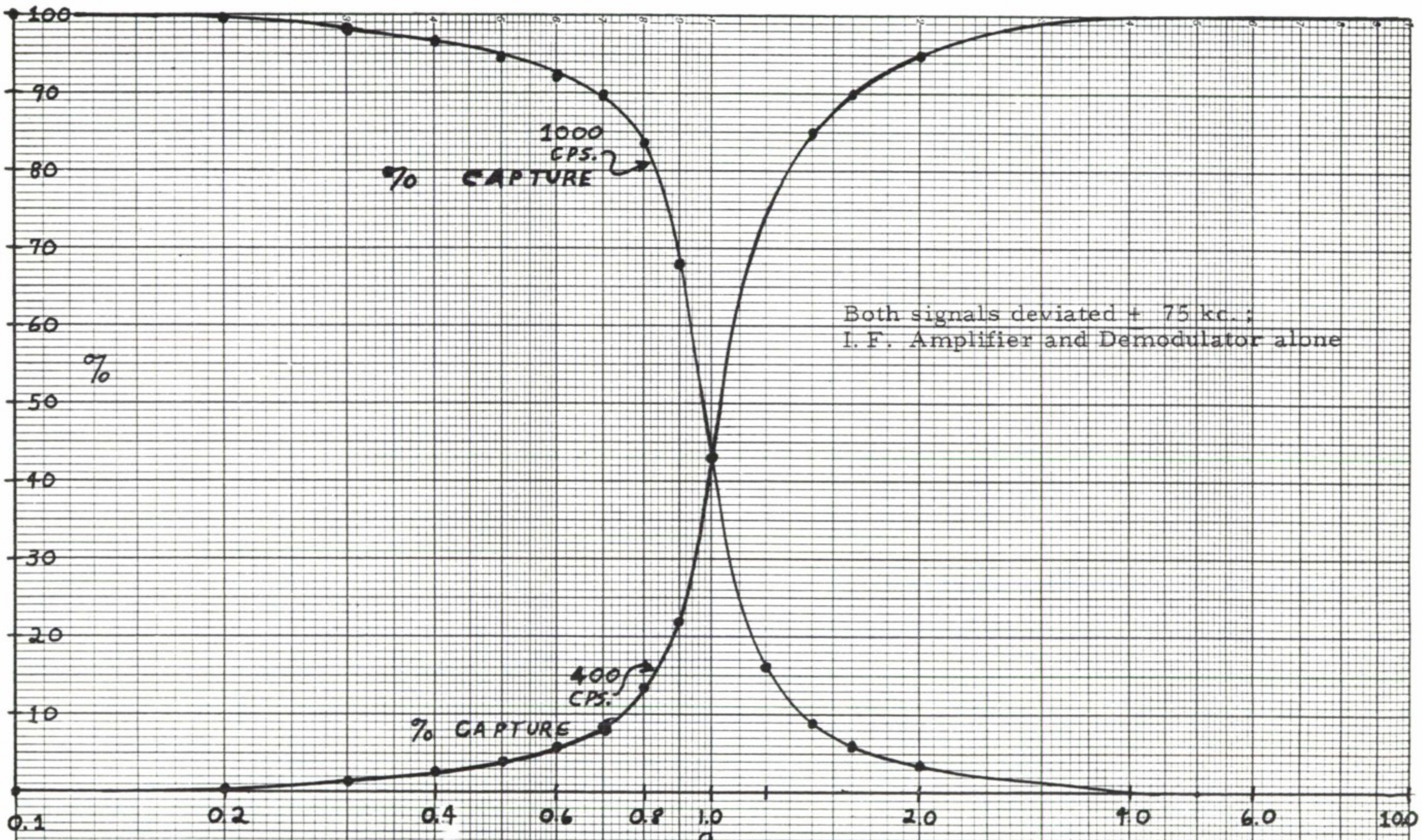


Figure 10: Demodulator Capture Plot Obtained by Lowering Limiter Time Constants and Reducing Discriminator Time Constant to 3 μsec.

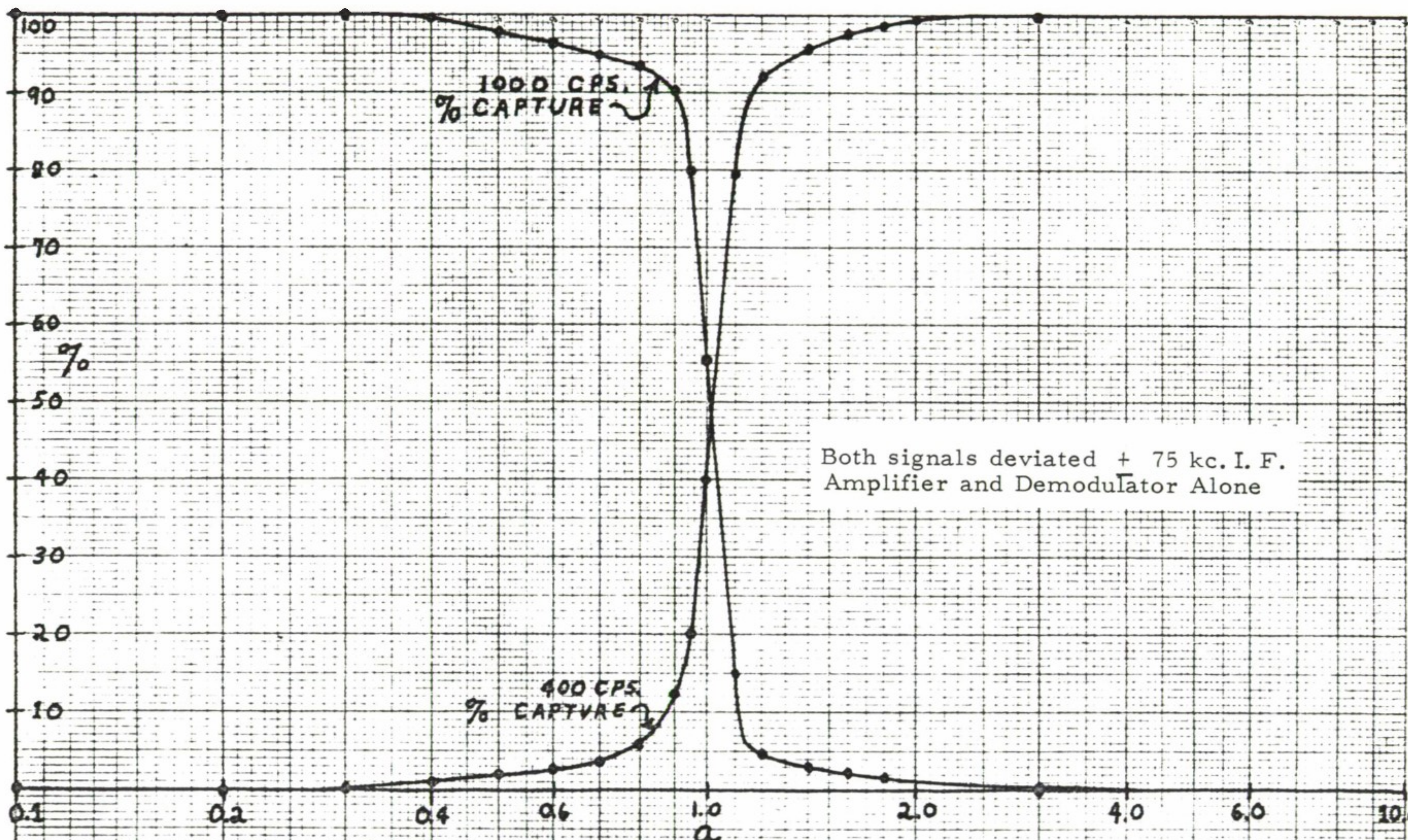


Figure 11 Circuit same as in Figure 10 except

900-kc Discriminator Transformer (Miller No. 1464-WB) substituted for original unit.

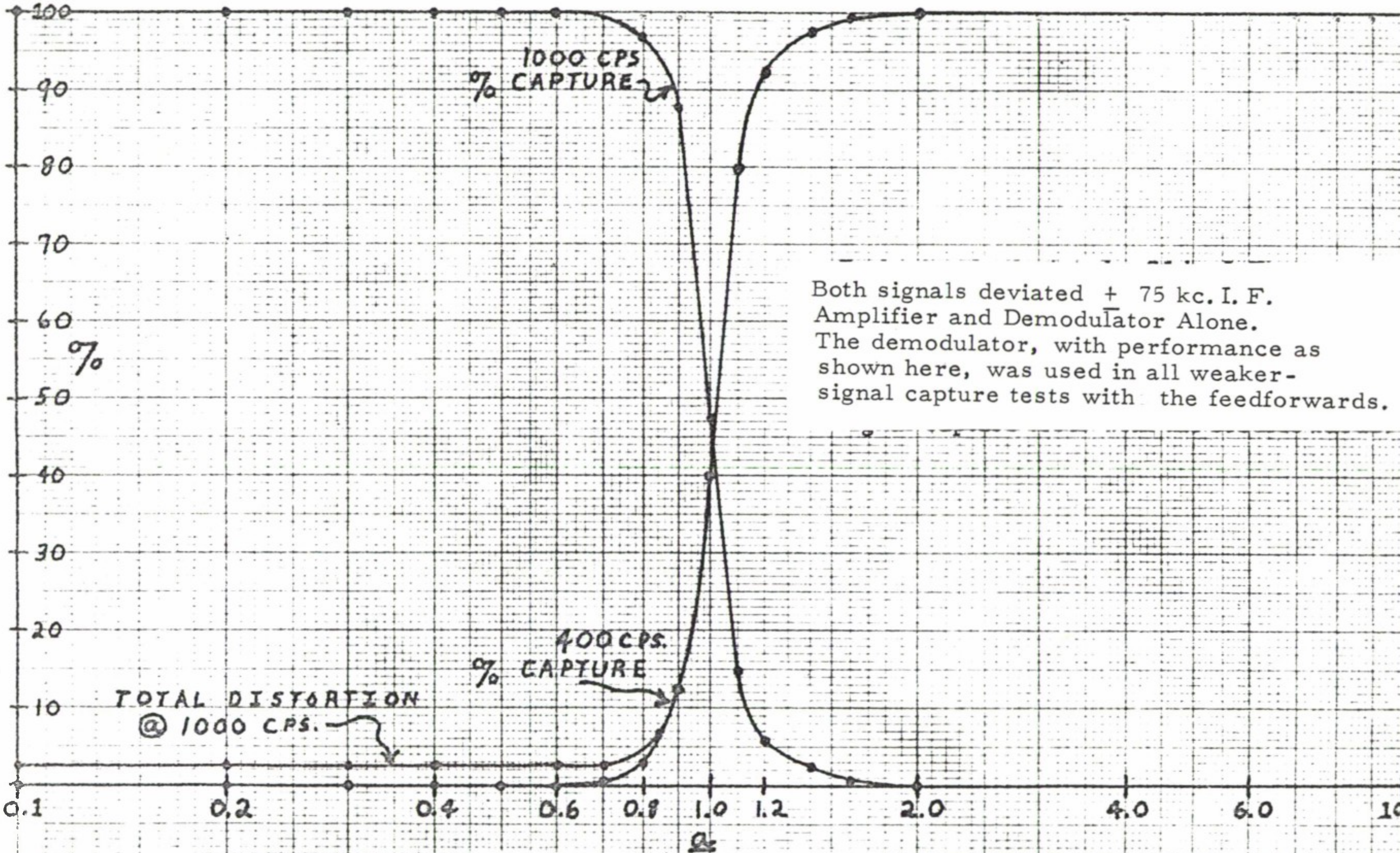


Figure 12 Circuit same as in Figure 11 except Discriminator Time Constant Lowered from 3 μsec. to 1.4 μsec.

Figure 12 is an example of the demodulator performance obtainable with simple circuitry and noncritical commercially available parts by careful attention to the really important design factors. Gutwein (11) obtained essentially equivalent performance by using the same discriminator circuit with three fast-acting 6BN6 limiters instead of the four pentode limiters used here.

The best approach to designing practical high-performance demodulators seems to be to use the widest bandwidth discriminator which can be conveniently built, considering requirements on sensitivity, audio hum and noise, and complexity. One to four narrow-band limiters followed by the usual wideband limiter should then be used ahead of the discriminator to improve capture performance.

The wideband discriminator transformer used in the experimental demodulator (5 to 6 I. F. bandwidths) is sold as an "off-the-shelf" commercial item, demonstrating its practicality. Its one disadvantage is its reduced audio output compared with that available from a narrow-band unit. If this reduced output should necessitate an additional audio stage in a receiver, design and construction of this one stage would be far simpler than adding one or more additional narrow-band limiters in order to obtain equivalent performance with a narrow-band discriminator.

The capture performance shown in Figure 12 is not a great deal better than that theoretically obtainable from a single wideband limiter, plus a discriminator of the bandwidth used. This seems to indicate that the three narrow-band limiters used are delivering nowhere near the interference-rejection performance theoretically obtainable from three ideal limiters. The conclusion is not too surprising, since the pentode limiters employed have many shortcomings: the shape of their limiter characteristics is poor; the interstage tuned circuits leave much to be desired; and their grid time constants are marginal; though they have been reduced as much as possible. Probably their worst problem is insufficient drive from one limiter to maintain saturation in the next for large a. Therefore, the performance of the demodulator could probably be improved somewhat without adding significantly to its complexity by the rise of better limiters.

The Transformer-Input Feedforward

Figure 13 is a schematic of the experimental transformer input feedforward. It employs pentode limiters quite similar to those in the modulator of Figure 4, and includes a pentode pre-limiter ahead of the feedforward proper.

The amplifier following the basic feedforward is included to raise the low-amplitude residual output signal from the feedforward proper to a level sufficient to drive the demodulator adequately. Use of the amplifier stage also makes it possible to use two double-tuned transformers instead of one in the filter following the feedforward. Commercial transformers are used as in the I. F. amplifier. The amplifier design is strictly conventional, using a variable-μ 6BA6 tube with adjustable cathode bias to provide control of amplifier gain. Screen voltage is supplied from a voltage divider to minimize its variation with cathode bias.

The feedforward amplifier uses the same basic circuit as the demodulator driver amplifier. Its gain control provides the operating control for the parameter "k". This basic amplifier design is used as a "building block" in all of the experimental feedforward systems to be described.

The center-tapped feedforward input transformer is a modified commercial narrow-band discriminator transformer. The modifications consisted of removing the coupling capacitor, adding tuning capacitance to the primary, and sliding the coils further apart to decrease the coefficient of coupling. A transformer carefully designed and specially constructed for the job would undoubtedly have been better; however, its construction would have also taken a great deal more time than modifying the commercial unit, and performance of the modified discriminator transformer seemed adequate to deomonstrate the feasibility of the circuit.

The A. M. detectors are included to allow frequency response curves of various parts of the system to be dynamically plotted, as explained in Chapter 5. They are designed to cause a minimum of circuit loading, and are wired in permanently. The basic detector circuit is also used in the other feedforwards.

Experimental Transformer-Output Feedforward

The transformer-output circuit of Figure 14 employs the same type of modified discriminator transformer as the circuit of Figure 13, but in a different manner. Note that no pre-limiter is included in this circuit and that a 6BN6 gated-beam limiter is used instead of a pentode

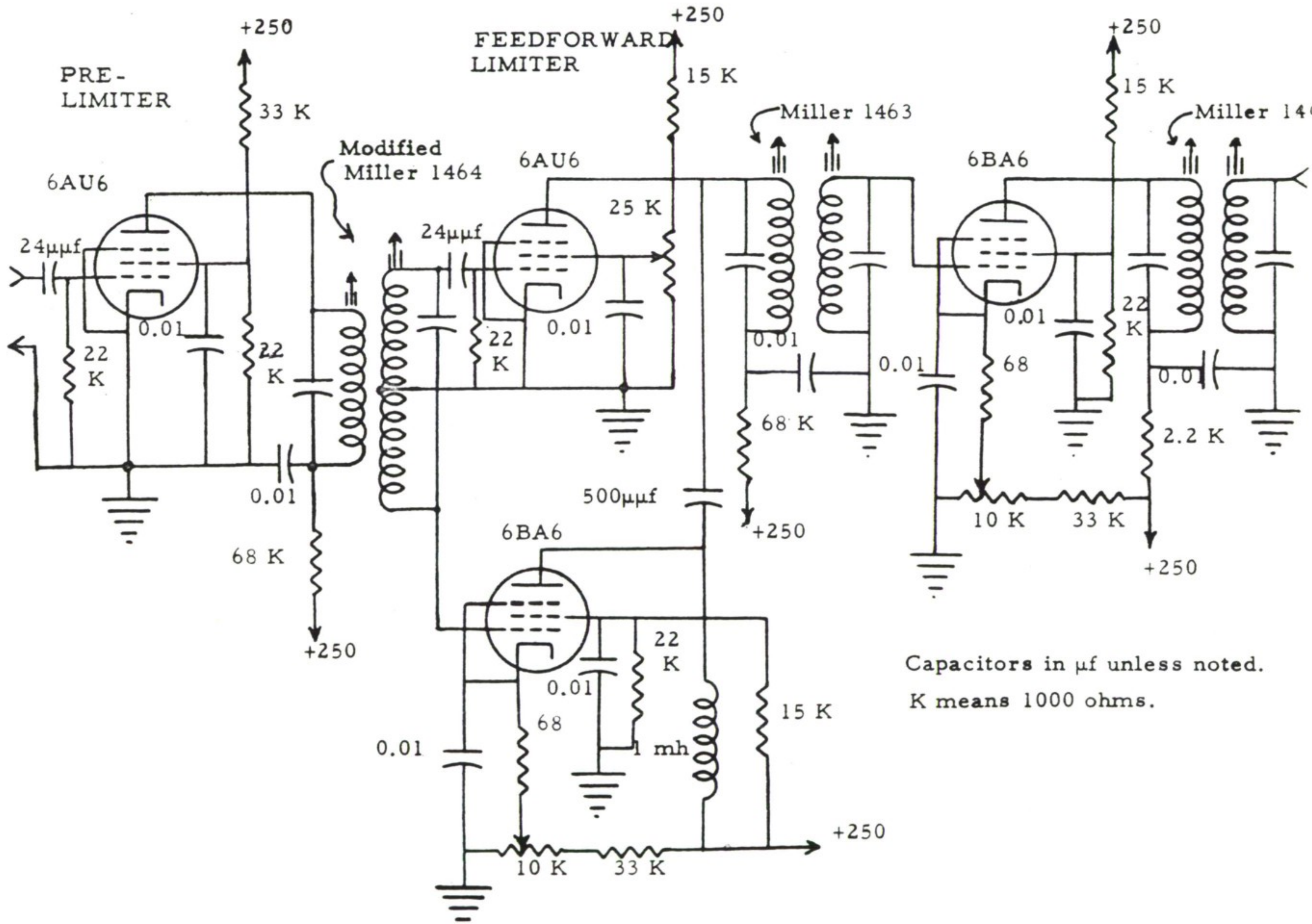


Figure 13: Circuit of the Experimental Transformer-Input Feedforward

limiter. Provision is included for independently adjusting the bias voltages on all three 6BN6 grids in order to obtain the best possible limiter characteristic. The amplifier circuits are identical to those of Figure 13.

Experimental Driver-Limiter Feedforward

The schematic of the experimental driver-limiter feedforward in its final form is shown in Figure 15. The basic limiter and amplifier circuits used are the same as those of Figure 14, phase opposition being obtained in a different manner. The driver-limiter circuit was first built using two pentode limiters, one as a pre-limiter; it was later modified to the circuit shown to obtain improved performance.

The only circuit feature not covered in descriptions of the other feedforward circuits is the plate circuit of the driver amplifier. The variable inductor (slug-tuned) resonates with circuit capacitance at the operating frequency of 10.7 mc.

The low limiter input impedance loads this low-C tuned circuit heavily; the 5600-ohm 6BA6 plate load resistor provides additional loading and swamps the non-linear limiter input impedance to some extent, since the limiter input impedance varies between about 5000 and 20,000 ohms depending on the input voltage. In practice, the phase characteristic of the low-Q tuned circuit was more important than its amplitude characteristic, which was quite broad. Detuning of the slug-tuned coil resulted in excessive phase shift and consequent cancellation of the stronger signal long before the reduced limiter drive caused any trouble.

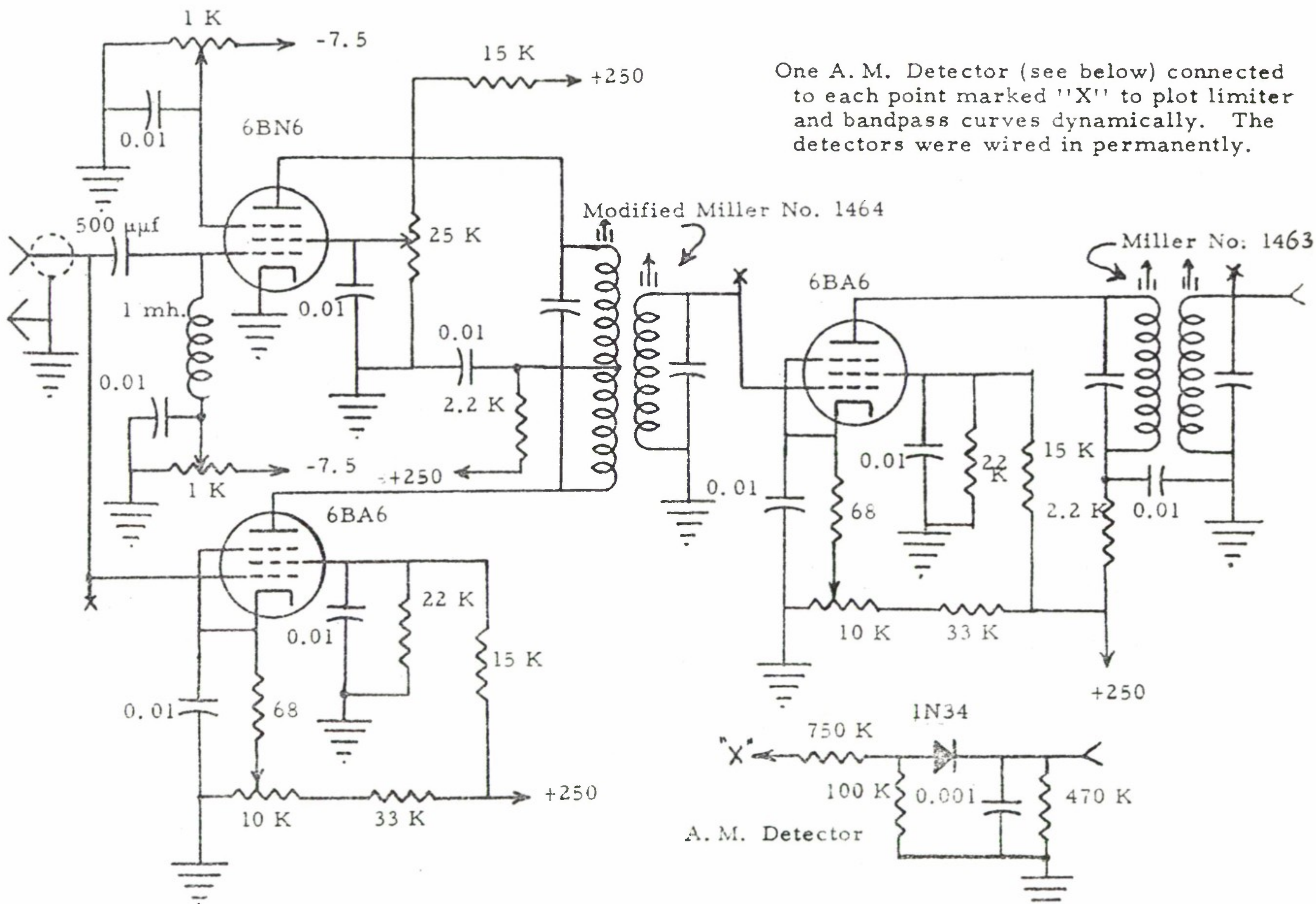


Figure 14: Circuit of the Experimental Transformer-Output Feedforward

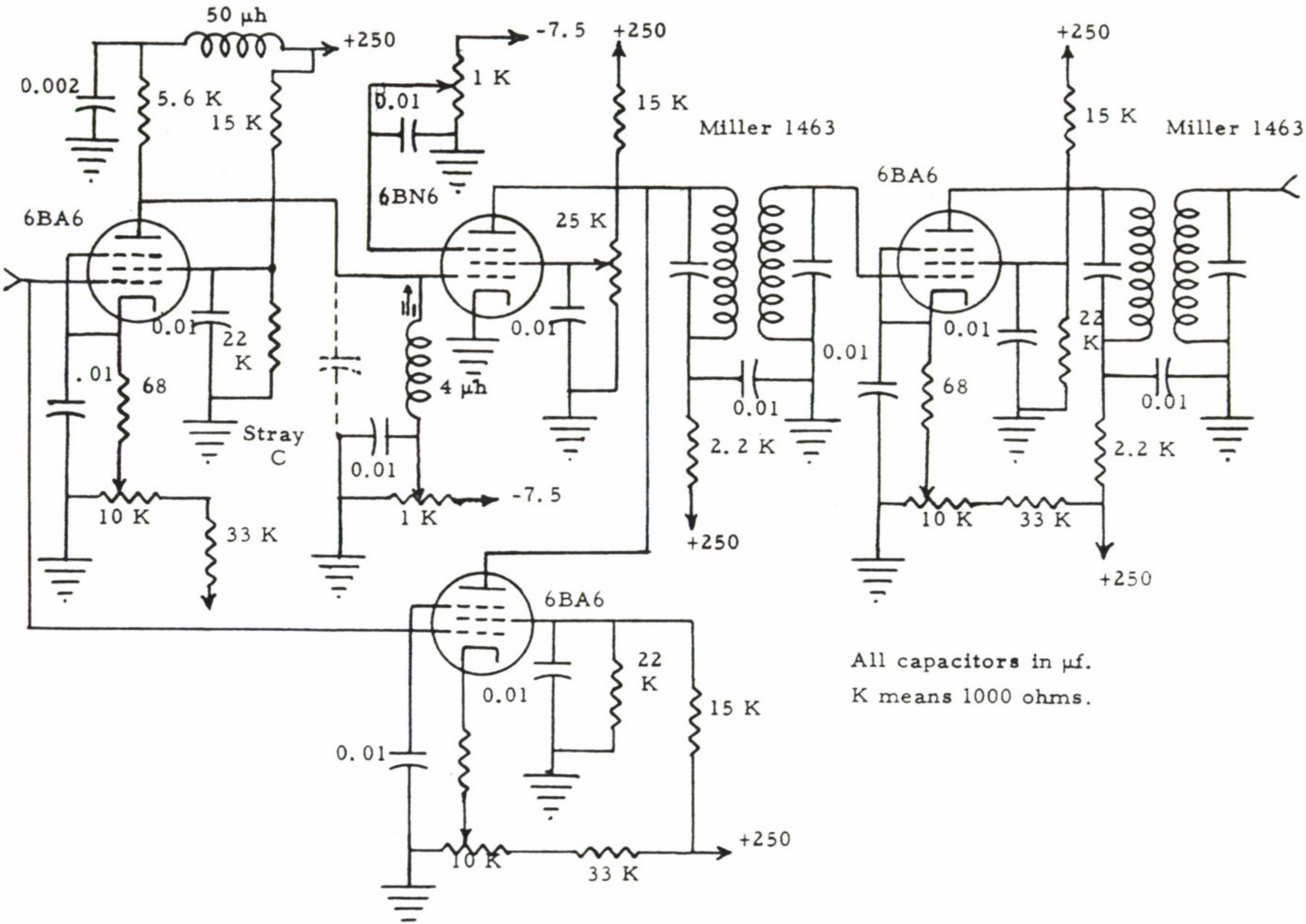


Figure 15: Circuit of the Experimental Driver-Limiter Feedforward

CHAPTER 5

THE EXPERIMENTAL MEASUREMENTS

The Experimental Setup

Figure 1 shows the arrangement used for experimental measurements on the laboratory model feedforward receivers. Two FM signal generators provide modulated signals at 10.7 mc with peak deviations up to $\pm$ 240 kc (normally $\pm$ 75 kc). The nominal output amplitude of the signal generators is continuously variable between 0.1 and $2X10^5$ microvolts. Both generators can be modulated by internal audio oscillators at frequencies of 50, 100, 400, 1000 or 5000 cycles; higher modulating frequencies are also provided but were not used. The generators can also be modulated by an external low-impedance audio source; an audio oscillator or a specially built modulator (Figure 2) is used for this purpose. The modulator allows direct speech modulation or modulation by a thyratron random noise generator or other source and includes provision for speech clipping and filtering such as is commonly used in communication transmitters.

The audio output from the feedforward receiver was monitored at all times by an oscilloscope which was extremely useful for initial adjustments and for determining in detail what was happening to the modulation waveform. A harmonic wave analyzer, essentially a tunable filter with a bandwidth of a few cycles, was used to examine the amplitude of individual frequency components, while total distortion measurements were made with an ordinary null-type distortion analyzer.

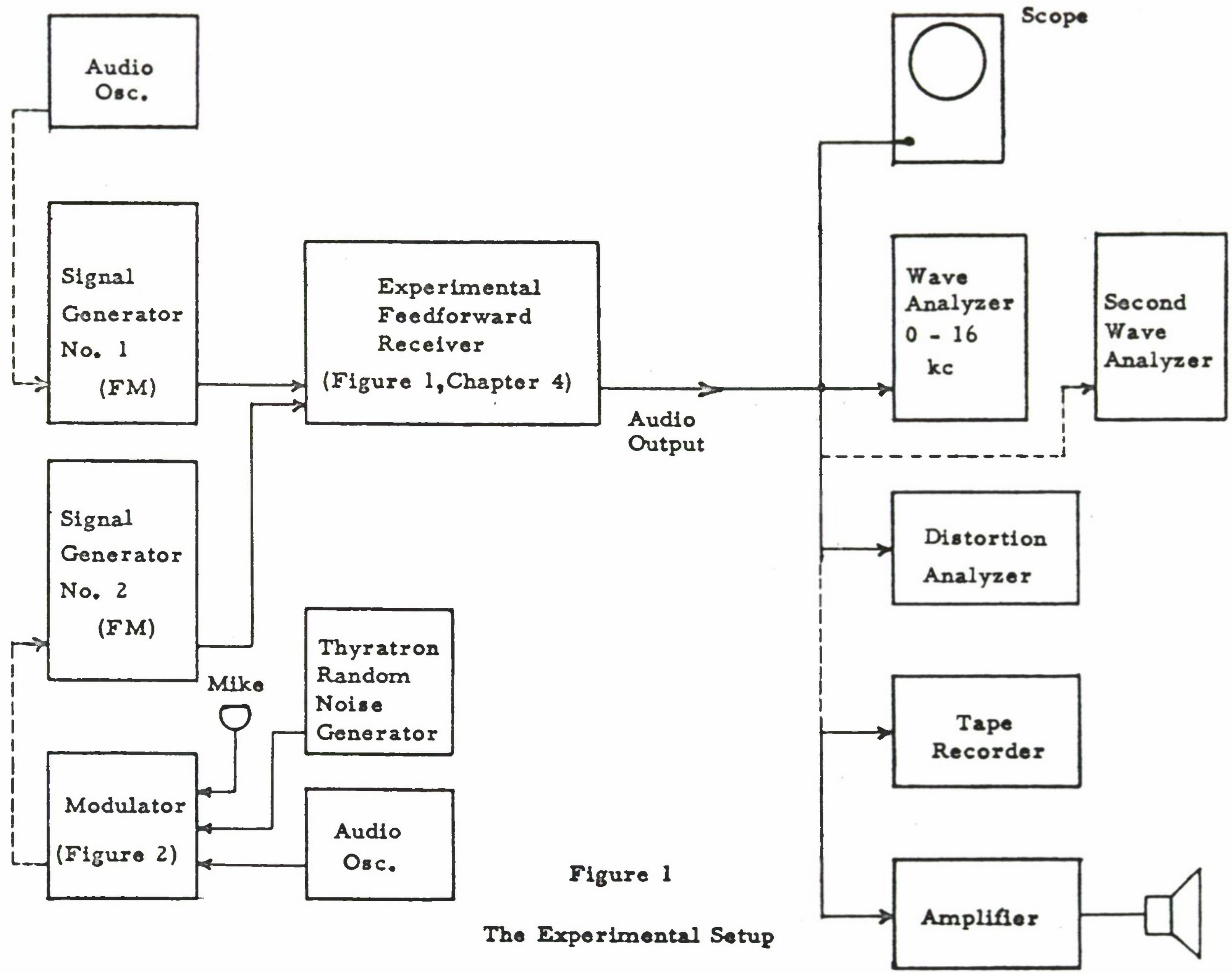


Figure 1

The Experimental Setup

Equipment Used in Setup of Figure 1

Signal Generators:

No. 1: Boonton 202-B

No. 2: Boonton 202-C

Both used with 203-C Univerters

Audio Oscillators:

Hewlett-Packard 200-B

Wave Analyzers:

General Radio 736-A

Distortion Analyzer:

Hewlett-Packard 305

Oscilloscope:

Either a Du Mont 304-H or a Tektronix 515, the latter being used for photographs.

A tape recorder and speaker amplifier were used for subjective listening tests.

Figure 3 shows the arrangement used to plot dynamically the frequency response curves. The method is standard, and has been described adequately elsewhere. Such an arrangement is essential when working with a feedforward receiver because of the importance of the passband shape of the various filters involved. The method can be used to plot the response curve of the single filter following a limiter independently of the other filters, because the limiter action removes the effect of the amplitude variations caused by preceding filters.

A similar method was used to plot dynamically the amplitude characteristics of limiters, as shown in Figure 4. This is a slight modification of the method used and explained by Gutwein [11]. Its major limitation is inability to plot limiter characteristics over a very wide range of input amplitudes due to the limited capabilities of the signal generator modulator, namely, the impossibility of linear 100% modulation in the negative direction. This limitation could be overcome to some extent by varying the signal generator R. F. output control to examine different portions of the limiter characteristic.

Measurement Procedures

Techniques for evaluating the performance of the feedforward receivers were in part developed as the experimental work proceeded, since, of course, no standardized procedures yet exist for measuring the performance of weaker signal capture receivers. Several of the measurement techniques were improved while the work was in progress;

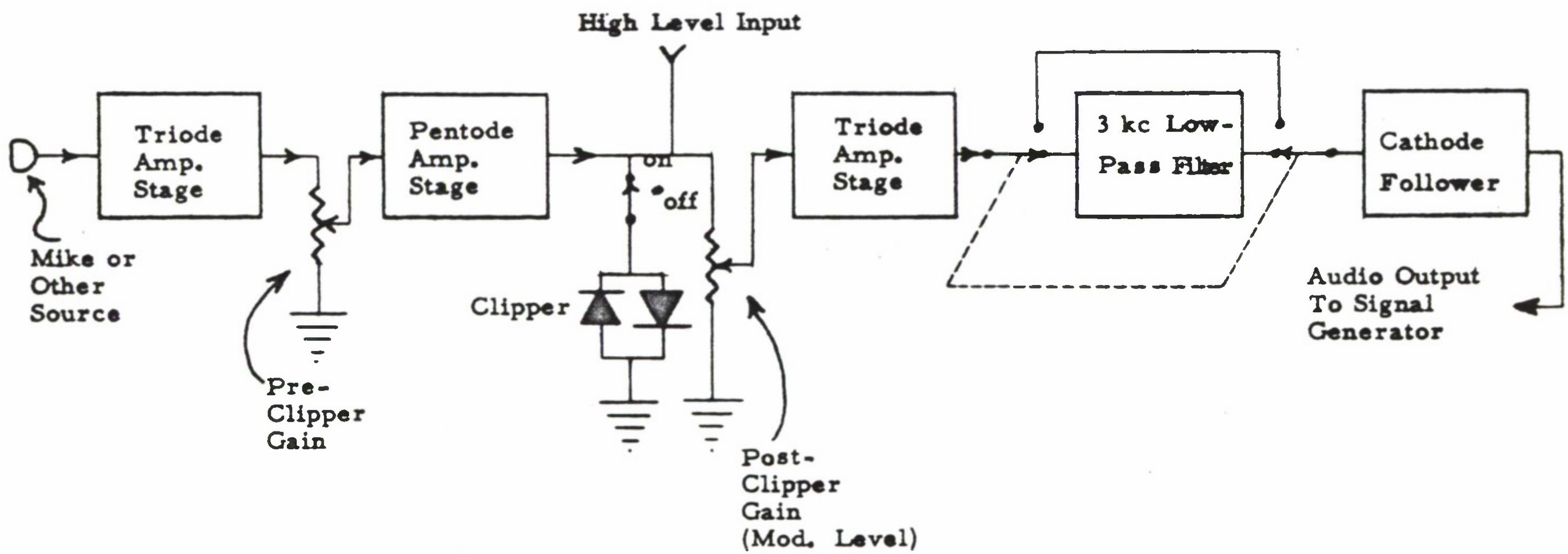


Figure 2

Block Diagram of the Signal-Generator Modulator

therefore, different procedures were used at different stages of the investigation. It is usually possible, however, to obtain some comparison between early results and those obtained later by slightly different procedures.

The so-called "capture plot" is one method for portraying graphically the performance of FM receivers designed to separate co-channel signals of different amplitudes. Figures 9 through 12 of Chapter 4 are examples of capture plots. They are obtained by feeding two signals of known amplitudes into the receiver input, the two signals being modulated by sinusoids of different frequencies. At each value of relative amplitude (interference ratio a), harmonic wave analyzers are used to measure the amplitudes of the two modulating frequencies at the demodulator output. The demodulator output amplitude at each frequency is plotted as a percentage of the value it would have if the signal in question occupied the channel without interference. This percentage is plotted vertically for each signal and is called "per cent capture". The interference ratio a is plotted on the horizontal axis. The capture plot thus presents a comprehensive picture of how well the desired signal modulation is captured as a function of a and what fraction of the modulation from the undesired signal leaks through at each value of a. Furthermore, both of these measurements are independent of the type of audio filtering and/or de-emphasis used in the demodulator, since they are expressed as percentages of audio amplitudes in the absence of interference.

The simple capture plot described above has one disadvantage; it gives only an approximate idea of the quality of the captured signal

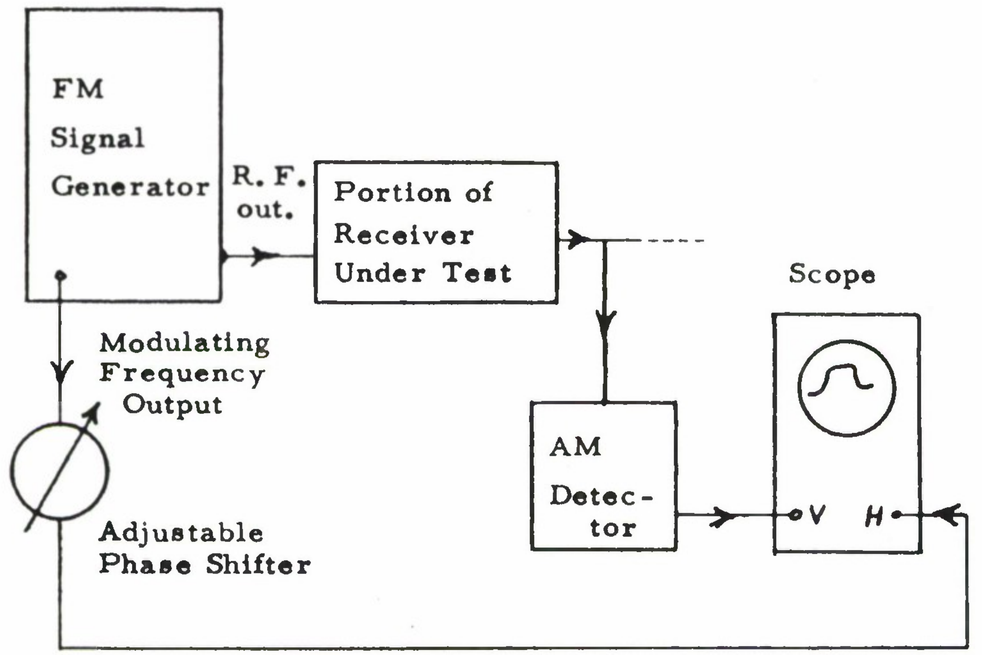


Figure 3

Method Used to Dynamically Plot Frequency Response Curves

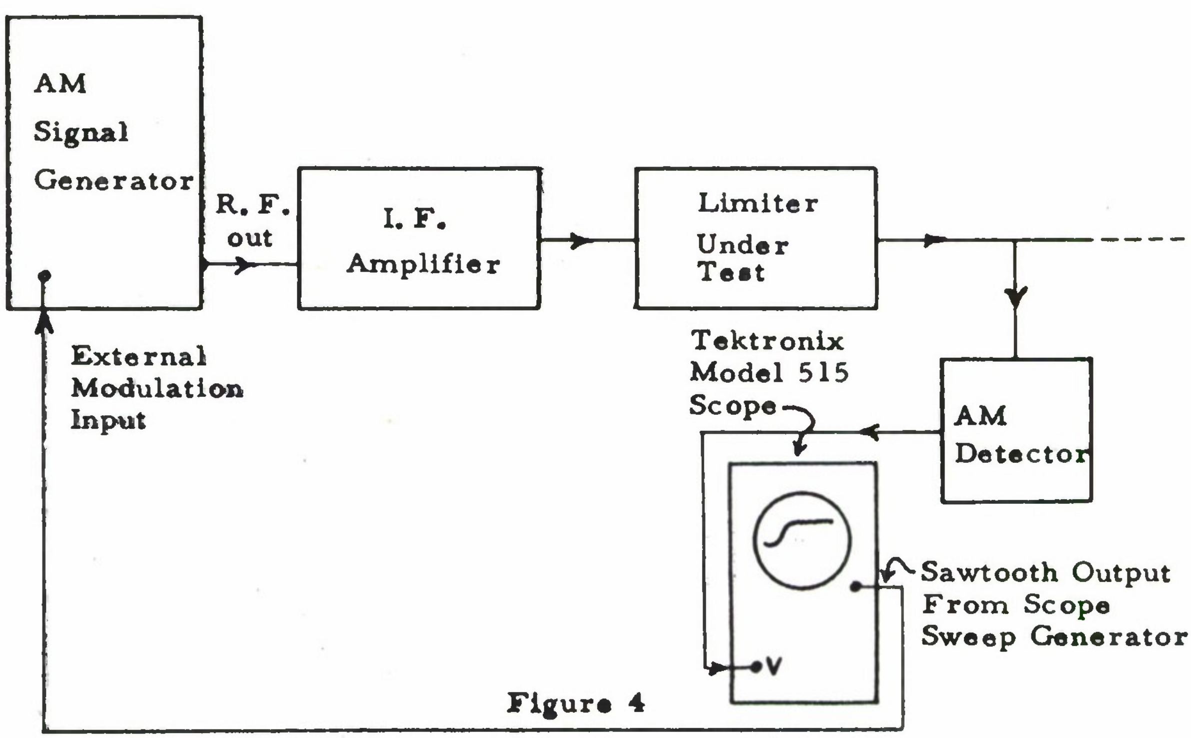


Figure 4

Method Used to Dynamically Plot Limiter Transfer Characteristics modulation. If total distortion as measured by a distortion analyzer is also included on the capture plot as a function of a, this defect is largely remedied. Total distortion is generally more important than per cent capture of interfering-signal modulation, especially since it was found possible to reduce interfering-signal modulation to less than 1% of its undisturbed value, other frequency components being much more prominent in the output and causing considerable distortion. The per cent total distortion depends on the kind of audio filtering used, as amply brought out in the data to follow. In obtaining a capture plot, the following procedure was followed:

(1) Set attenuator dials of signal generators No. 1 and No. 2 at some convenient value such as 2000 μ volts.

(2) Adjust the generators for equal output and substantially equal frequency by watching the interference pattern at the discriminator output with both generators unmodulated and K = 0. Equal output is indicated by maximum amplitude of the spiked interference pattern; the spike repetition frequency, being equal to the difference frequency between the two signals, is adjusted to a minimum of a few cycles per second.

(3) Set the attenuator dial of generator No. 2 to a minimum. Modulate generator No. 1 with the desired modulating frequency for the stronger signal. Tune one wave analyzer to this frequency and set its input attenuator for a meter reading of 100%, corresponding to interference-free reception.

(4) Repeat step 3 with generator No. 1 set for minimum output and generator No. 2 modulated at the desired weaker, signal modulating frequency, another wave analyzer being tuned to this frequency and calibrated as above.

(5) Reset the attenuator dial of generator No. 1 to the reference value of 2000 μ volts. Set up the desired initial value of *a*, read from the attenuator dial of generator No. 2 by simple arithmetic; for example, 800 μ volts correspond to an *a* of 0.4.

(6) Adjust the receiver for best capture performance and read the two values of per cent capture directly from the meters of the wave analyzers. Total distortion is measured by the distortion analyzer.

From this point on, two alternate procedures may be followed resulting in two different types of capture plots. One method is to vary the amplitude of the weaker signal generator to obtain various values of *a* between zero and unity, recording data at evenly spaced values of *a*, the adjustments of the receiver all being left fixed at some compromise setting. The resulting capture plot indicates how well the receiver works with varying *a* for a constant level of stronger signal input and fixed adjustments.

In the second method, all important receiver adjustments are carefully reset for optimum performance at each value of *a*. A capture plot made in this way is an indication of the performance which could be obtained from a receiver in which no detrimental second-order effects occurred due to variations in a and which had a control system capable of maintaining the proper value of K as a varied.

A few plots were made in which only K was readjusted for each value of a, the other controls being set at some compromise adjustment. These plots indicate the performance that the receiver would actually be capable of if provided with a control system to optimize K under all conditions.

Initially, capture plots were made "double-ended" so that a extended to values greater than 1, the originally weaker and stronger signals exchanging roles for $a > 1$. The only advantage that results from including the region $a > 1$ is that the behavior of the receiver is measured with changing stronger-signal amplitude and with an interchange of modulating frequencies. The dynamic range of the receiver is of secondary interest in seeking to determine the basic potential of the feedforward technique and dependence of receiver performance on modulating frequency, if desired, may be fully investigated separately. Therefore, the double-ended capture plot was soon abandoned and only values of a less than 1 were considered. The modulating frequencies were standardized at 400 cps for the weaker signal, 1000 cps for the stronger.

Audio Filtering

As explained in Chapter 4 the demodulator as originally built included a 3 kc low-pass filter which could be switched in or out and R-C de-emphasis networks with time constants of 75 μseconds and 750 μseconds, either of which could be switched in alone or in combination with the low-pass filter. These various devices were included merely because they represented standard practice in various types of FM systems. The 75 μ second de-emphasis is standard in broadcast receivers, while the 3 kc low-pass filter is often used in communications equipment along with a de-emphasis of 6 db/octave, maintained within 3 db over the range 300 cycles to 3 kc. (750 μ second de-emphasis)

Early capture plots were made with 750 μ second de-emphasis plus the 3 kc low-pass filter, since this heavy filtering gave the lowest distortion figures when capturing 400 cycle weaker-signal modulation with 1000 cycle modulation on the stronger signal. As results improved, later plots were made with 75 μ second de-emphasis alone, in hopes of producing a system of acceptable distortion levels using broadcast-type standards throughout. This was not achieved, and 750 μ second de-emphasis was again used in a few plots, this time without the filter, which hardly made enough difference to justify its use.

Although de-emphasis was used in the receiver audio section for the initial tests described above, no attempt was made to use pre-emphasis in the signal-generator audio section. Since only one modulating frequency was involved at each generator, the use of pre-emphasis would have changed only the value of peak deviation of the signals. In order to obtain a preliminary indication of feedforward receiver performance to be expected, without going to the trouble of setting the deviation of the two signal generators according to some pre-emphasis curve, the first tests were conducted with full nominal peak deviation ($\pm$ 75 kc) on both signals, sinusoidal single-frequency modulation being used as explained above.

The first test in which weaker-signal modulating frequency was varied was also made with "flat" response in the signal-generator audio section; both signals were thus fully modulated at all times. In practice, of course, a transmitter with a flat audio response would not be used with a receiver which included audio de-emphasis; however, the test was conducted in this way for the sake of convenience in obtaining a preliminary estimate of the effect of varying weaker-signal modulating frequency.

The results of this initial test are shown in Figure 20. The distortion at the higher weaker-signal modulating frequencies was found to be considerably worse than at the previously used frequency of 400 cycles. The reason is apparent: the de-emphasis filter attenuated the higher modulating frequencies heavily while favoring distortion components at lower frequencies. It was reasoned that the use of pre-emphasis in the signal-generator audio would merely reduce the peak deviation for the lower modulating frequencies, having little effect on the distortion of the higher modulating frequencies; this conclusion was later confirmed experimentally, as will be described. It was tentatively decided that the use of flat transmitter audio response and a flat-topped audio bandpass filter in the receiver would provide a better compromise over the speech band in reducing the distortion on captured weaker-signal modulation than would the conventional pre-emphasis -- de-emphasis system. Accordingly, the audio section of the demodulator was redesigned around a bandpass filter, as described in Chapter 4.

The tentative decision to use a bandpass receiver audio filter and flat transmitter audio was fully justified by experiment, as shown later in this chapter; all subsequent measurements were then made using the bandpass filter. However, time was not available for the tedious work of re-measuring all previously obtained capture plots with the new audio system; a few points only were measured to provide some basis for determining what difference the new audio filter would make in distortion figures.

The account of the evolution of audio filtering techniques is included to explain the use of different audio filters in obtaining data taken at different times. It is important to note that "per cent capture" figures are unaffected by changes in audio filtering, and provide an excellent criterion for comparing systems whose performance was measured with different types of audio filters.

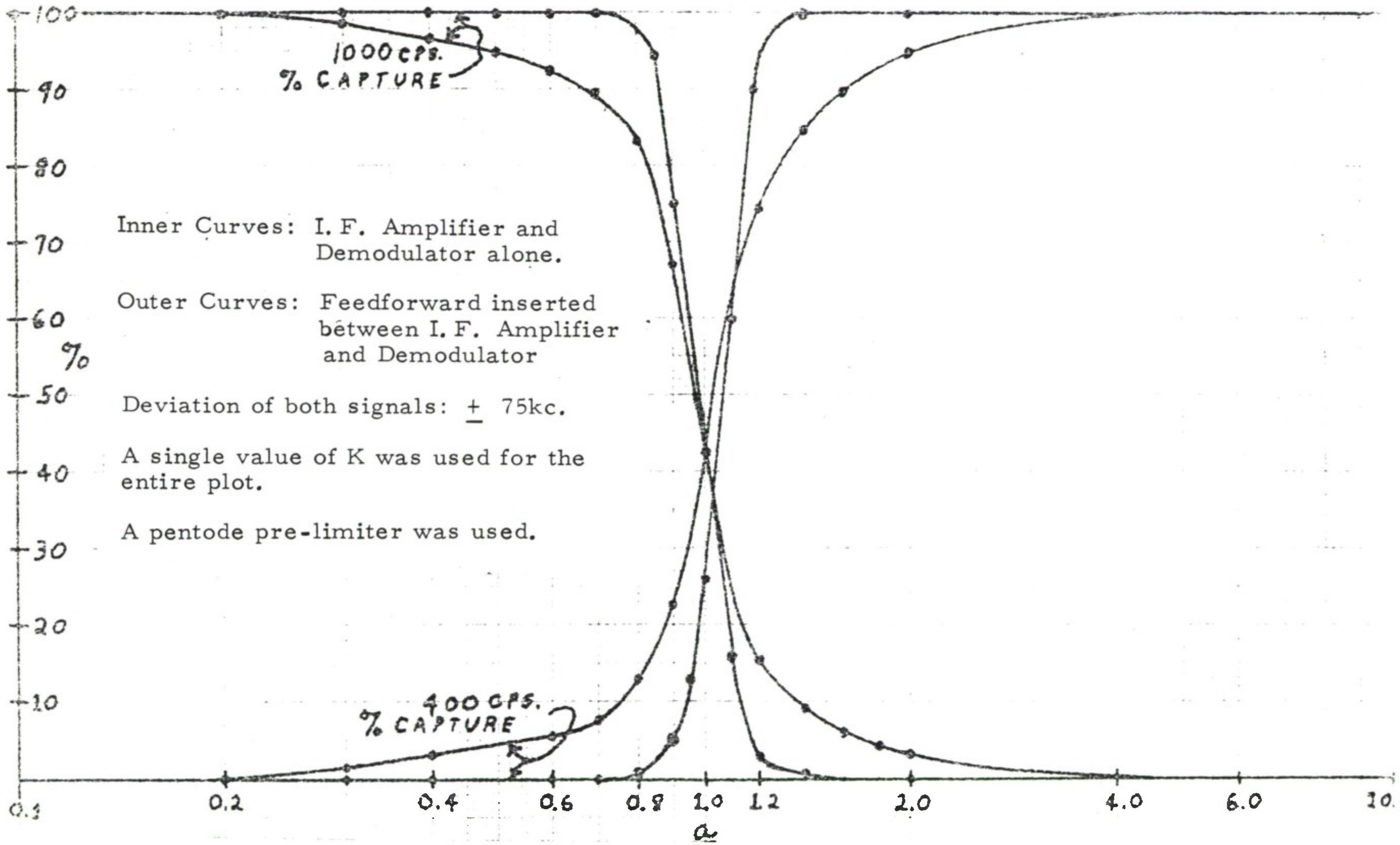
Results of Experimental Measurements

The Transformer-Input Feedforward

Figures 5 through 10 are capture plots obtained using the transformer-input feedforward. All were made with pentode limiters in the feedforward proper and a pentode pre-limiter. Since they were the first capture plots made for this investigation, distortion measurements were usually not included.

Figure 5 shows the improvement in stronger-signal capture obtainable with the feedforward. The inner dotted curves are the curves of Figure 10 of Chapter 4 and represent the performance of the demodulator alone in an early stage of its development. The outer curves were obtained by inserting the feedforward between the I. F. amplifier and the demodulator and adjusting K for best capture, a single value of K being used for the entire plot.

Figure 5



Enhancement of Demodulator Stronger-Signal Capture Performance by Transformer - Input Feedforward

Figure 6 shows receiver performance with K set for optimum capture of the weaker signal at an a of 0.5. Performance of course falls off on either side of a = 0.5; note that the deterioration occurs much more rapidly for a $<$ 0.5 than for a $>$ 0.5 because of the more stringent requirements on K for small a, as explained in Chapter 2. The plot is asymmetrical because of amplifier overload and poor limiter performance at the large input signals which occur for a $>$ 1.

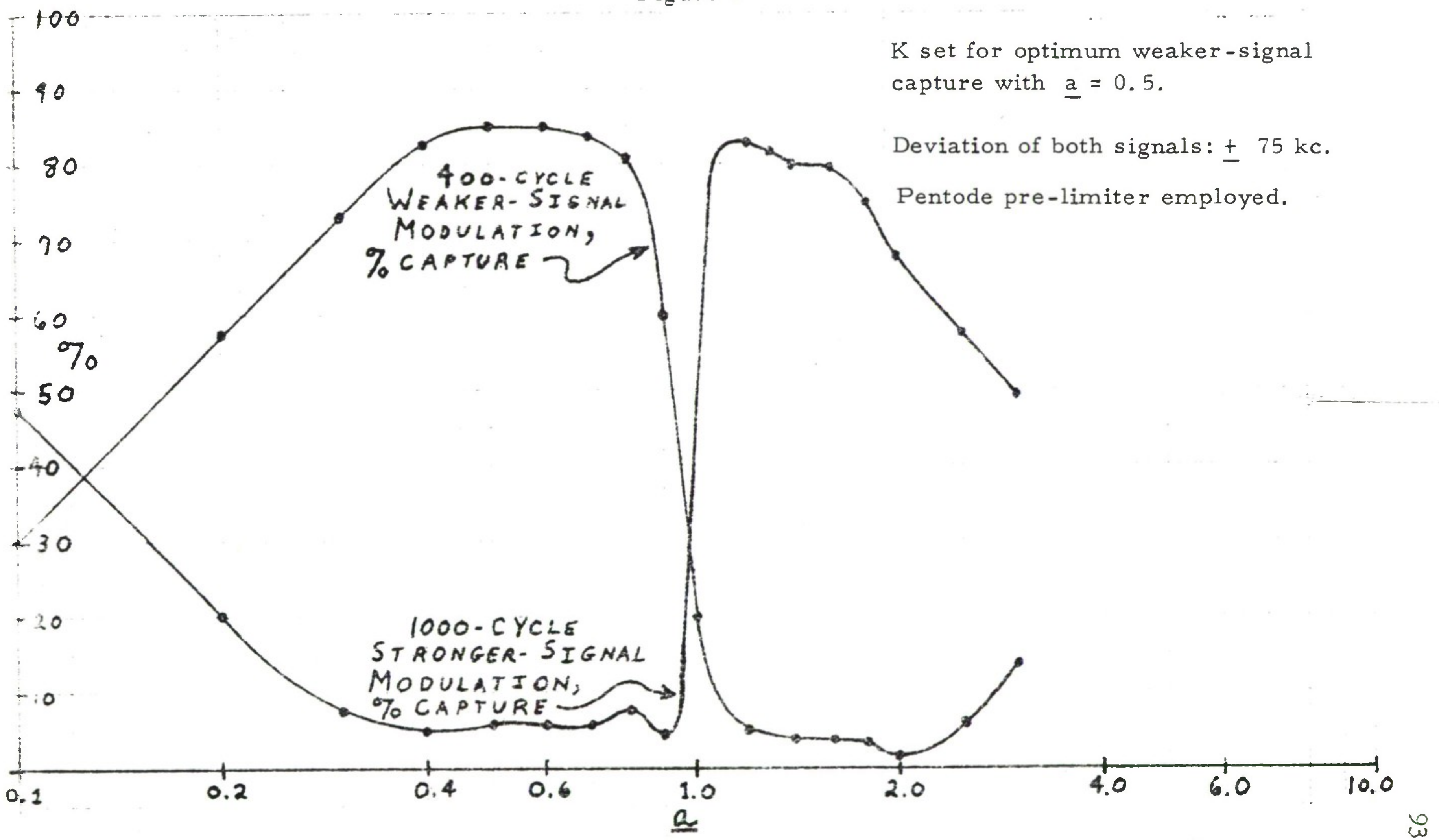
Figure 7 was obtained by re-aligning the receiver and optimizing the value of K for each a. The improved performance at high input signal levels was obtained at the expense of that for smaller signals.

Figure 8 shows somewhat improved weak-signal capture performance over that of Figure 7, obtained by careful re-alignment of the post-feedforward filter to obtain a flatter curve. Figure 9 indicates further improvement obtained by a more careful alignment of the entire receiver. In both of these plots, K was optimized for every a.

Figure 10 represents the best capture performance obtained from the transformer-input feedforward although the symmetry of the plot is none too good. Figure 11 shows the response curves of various portions of the system at the time the plot was made, and indicates the importance of flatness in the curves at small values of a. Note the very slight improvement in the flatness of the curves of Figure 11-B over those of Figure 11-A and the resulting improvement in capture performance shown in Figure 10.

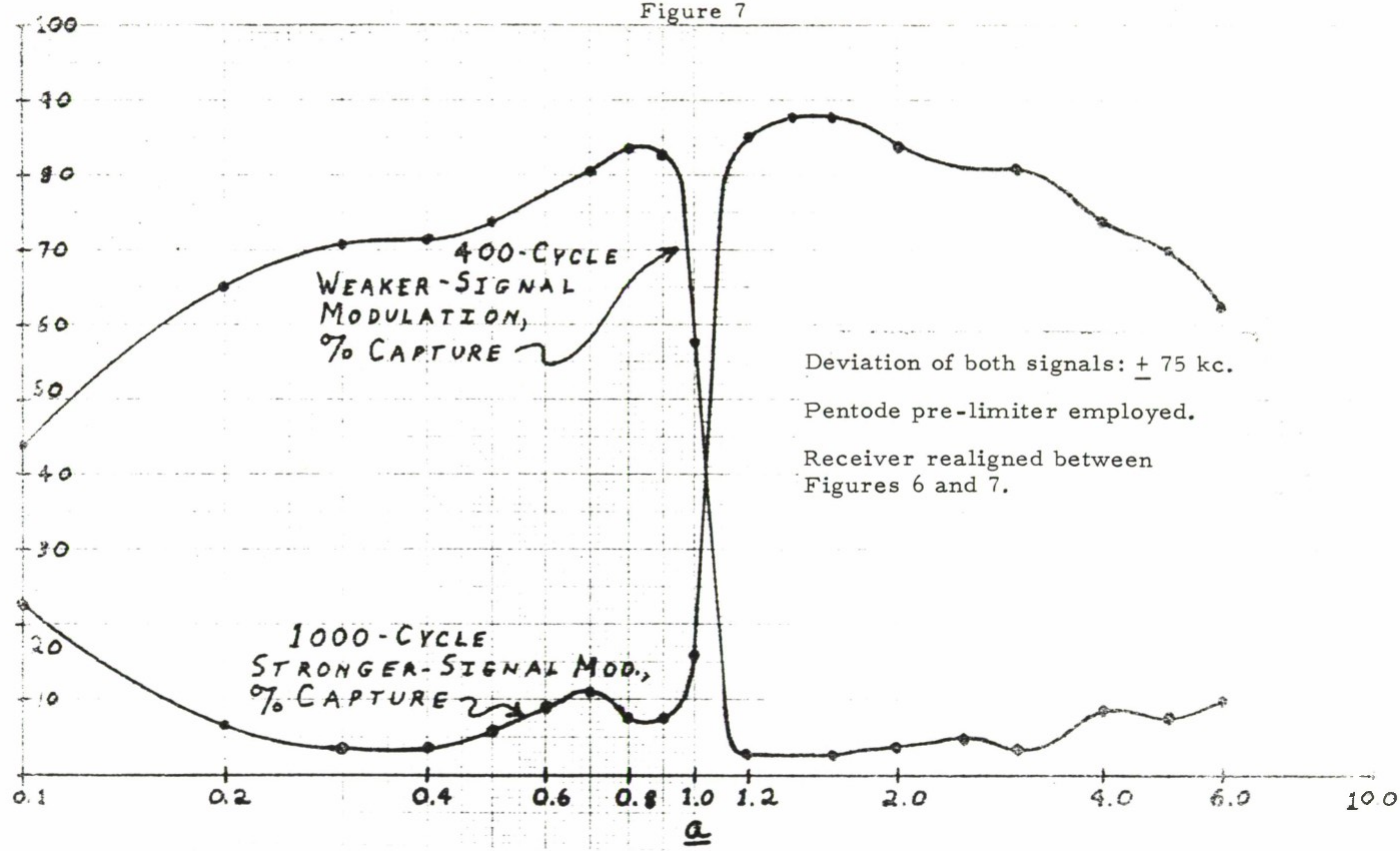
Figure 11-C shows the appearance of the recovered 400 cycle weaker-signal modulation with various types of audio filtering. The

Figure 6



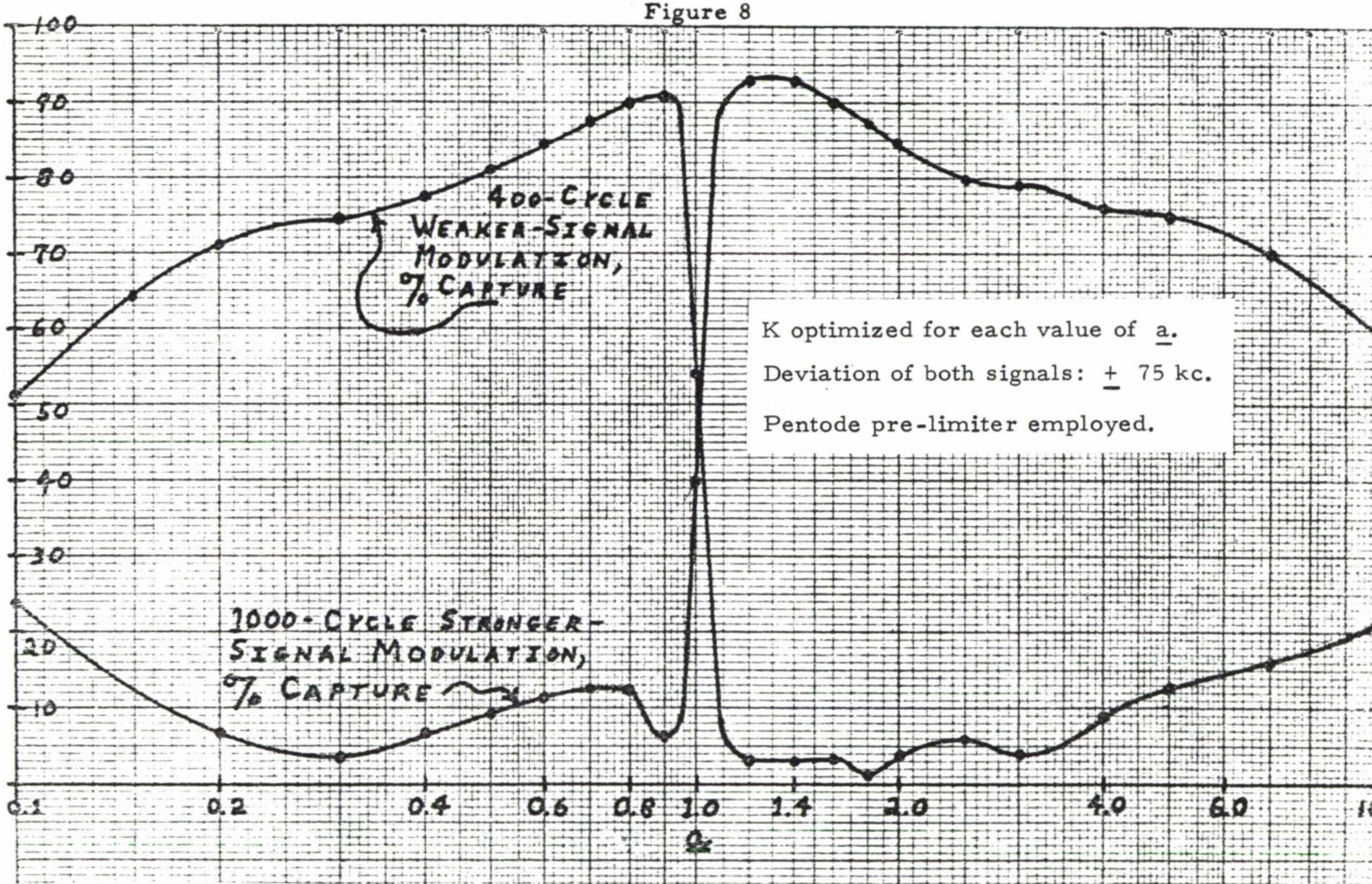
Weaker-Signal Capture Performance of Transformer-Input Feedforward with Fixed Value of K

Figure 7



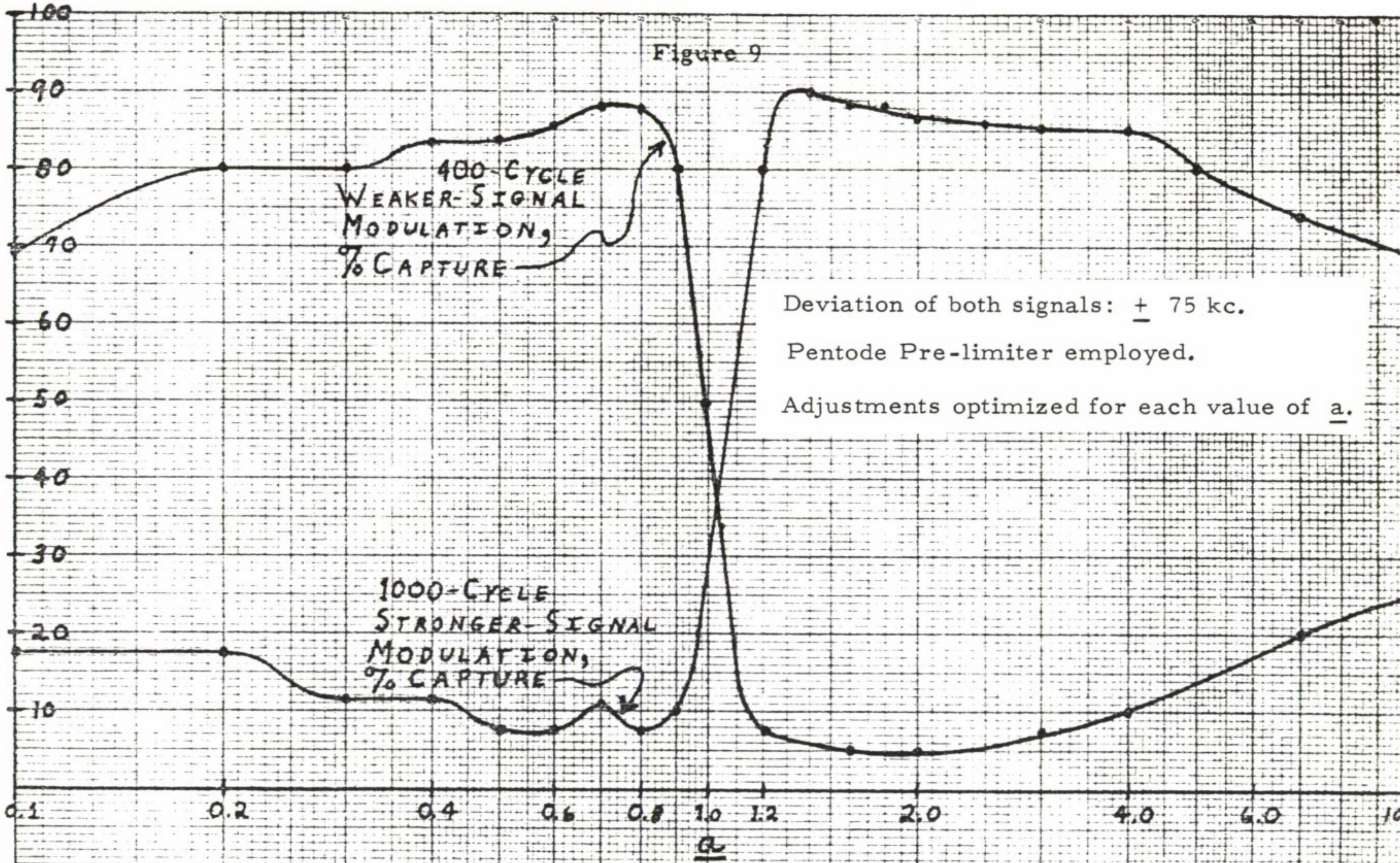
Weaker-Signal Capture Performance of Transformer-Input Feedforward; K Optimized for Each Value of a

Figure 8



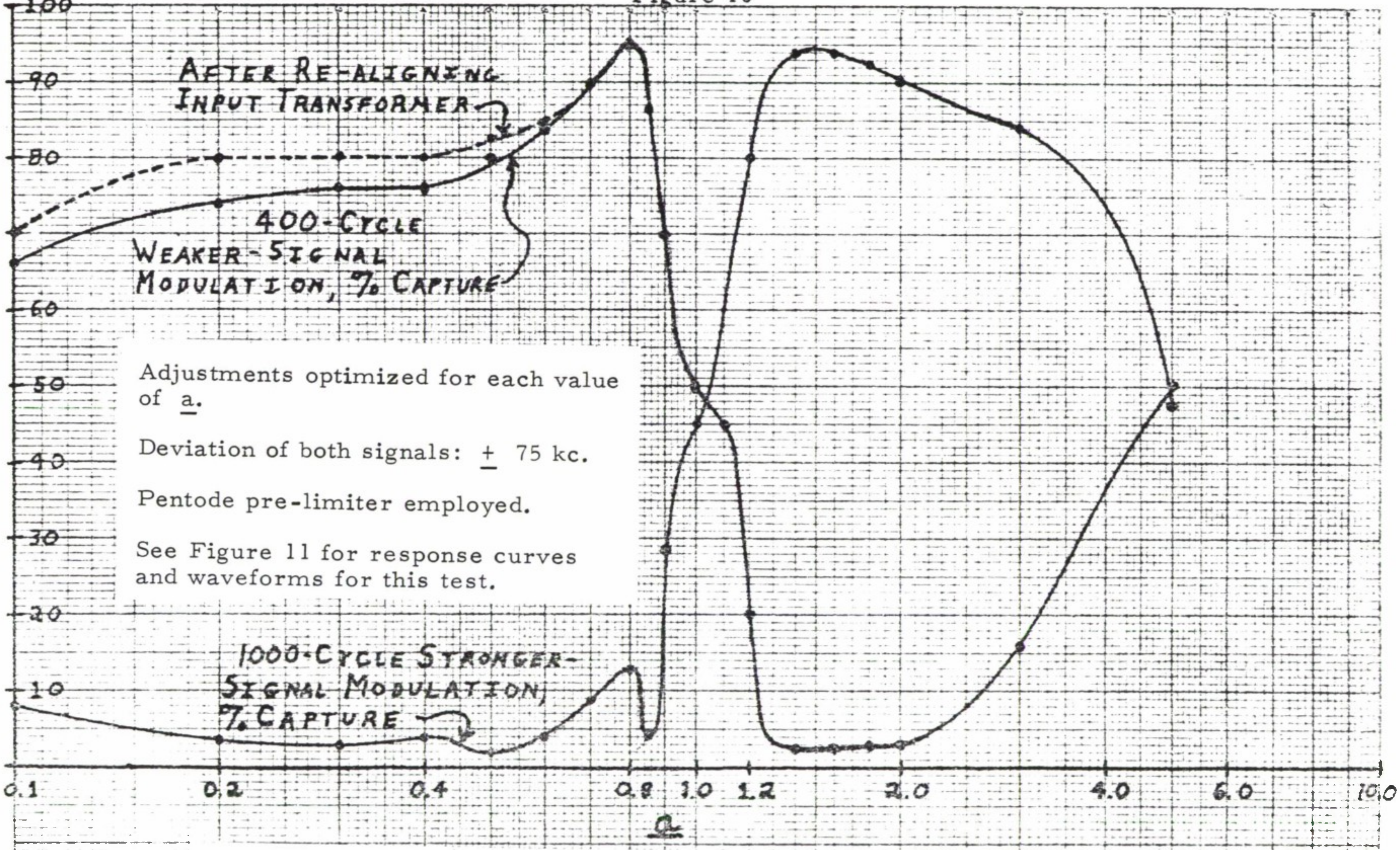
Improved Weaker-Signal Capture Performance with Better Alignment of Post-Feedforward Filter

Figure 9

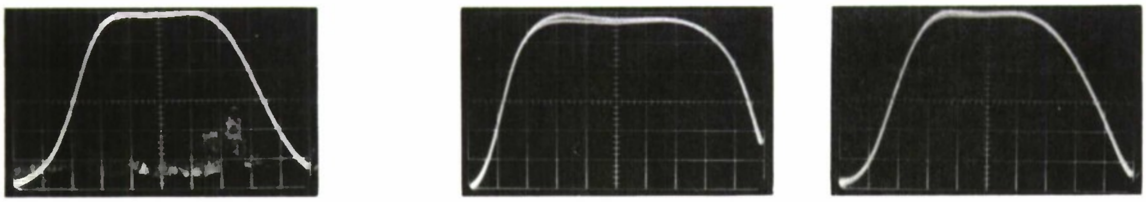


Improved Capture Performance for Small a obtained by Careful Alignment of Entire Receiver

Figure 10



Best Weaker-Signal Capture Obtained Using Transformer-Input Feedforward

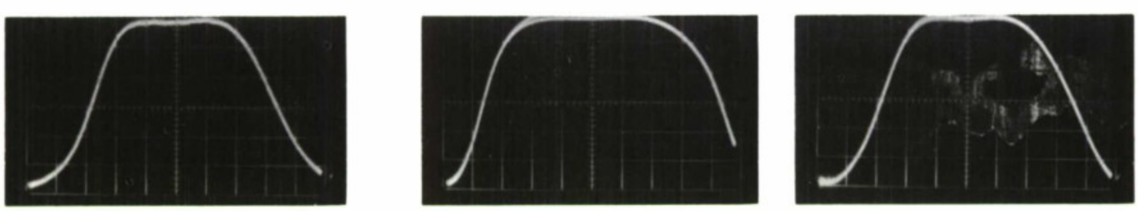


I. F. Amplifier | Feedforward Input Transformer | Post-Feedforward Filter

The vertical scale is linearly calibrated in relative amplitude. The horizontal scale is frequency, 40 kc. per division.

Figure 11-A

System Response Curves For Solid Per cent-Capture Curve of Figure 10

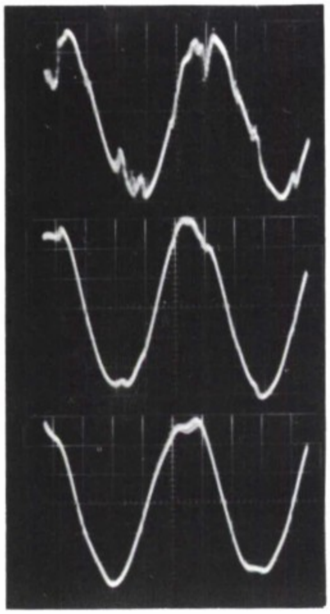


I. F. Amplifier | Feedforward Input Transformer | Post-Feedforward Filter

Scales same as above.

Figure 11-B

System Response Curves For Dotted Per cent-Capture Curve of Figure 10
(After Re-alignment)



75 μ second de-emphasis alone.
Distortion approximately 15%

750 μ second de-emphasis alone.
Distortion approximately 10%

750 μ second de-emphasis plus 3 kc.
low-pass filter.

Pictures taken at $\underline{a}$ = 0.7. 400 cycle weaker-signal modulation shown, at 90% capture. Stronger signal modulated at 1000 cycles; 9% capture of 1000 cycle modulation. Both signals deviated $\pm$ 75 kc. with center frequencies within a few cycles of each other (co-channel signals).

Figure 11-C

Appearance of Captured Weaker-Signal Modulation In Test of Figure 10 photos were made at the same time as the plot of Figure 10 at an a of 0.7, the point of best performance. The top waveform represents a distortion of 15% with 75 μ second de-emphasis.

The capture plots of Figures 5 through 11 illustrate the importance of flat frequency-response characteristics in the filters of a feedforward receiver and the necessity for exact alignment. They show that a very definite improvement in performance can be obtained by only a very slight re-alignment. The improvement thus obtained is most marked for small a, as predicted in Chapter 2.

The Transformer-Output Feedforward

Figure 12 is the first capture plot obtained with the transformer-output feedforward of Figure 14 in Chapter 4. The distortion figures, rather low for $0.2 < a < 0.8$, were obtained with 750 μsec de-emphasis and low-frequency rolloff, which rather favors the 400 cycle modulation used. Figure 13 shows improved results obtained with more careful alignment.

Figure 14 was obtained with the bandpass speech filter in the audio instead of the heavy de-emphasis. Although Figures 12 and 14 were measured at different times, their per cent capture curves are substantially the same, allowing comparison of the bandpass speech filter and the heavy de-emphasis under similar conditions. Use of the bandpass filter instead of de-emphasis increases 400 cycle distortion from 10% to about 25% in the middle range of a; however, it represents a better compromise over the entire speech band, as brought out later. Figures 13 and 15 allow the same comparison of audio filtering methods;

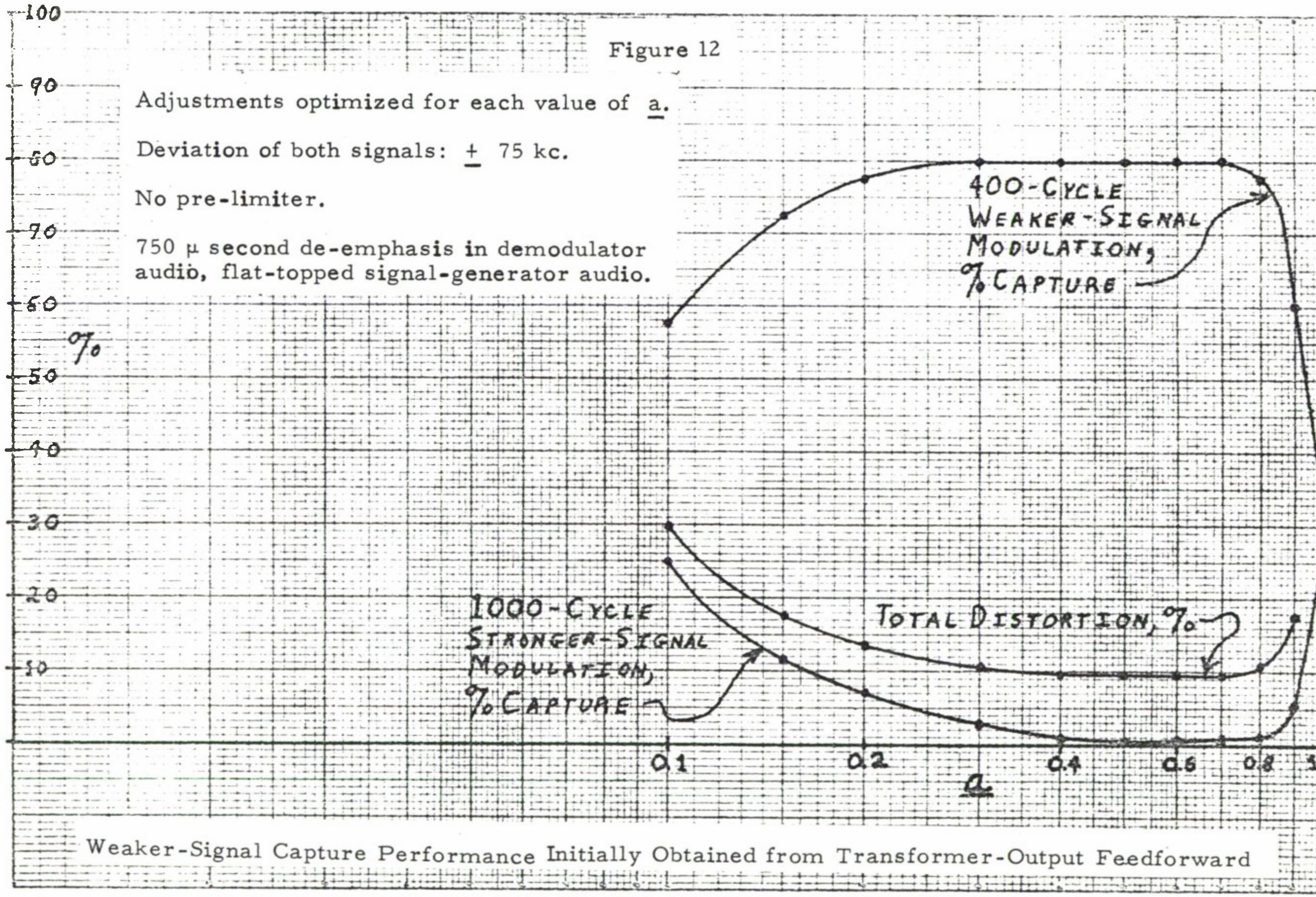
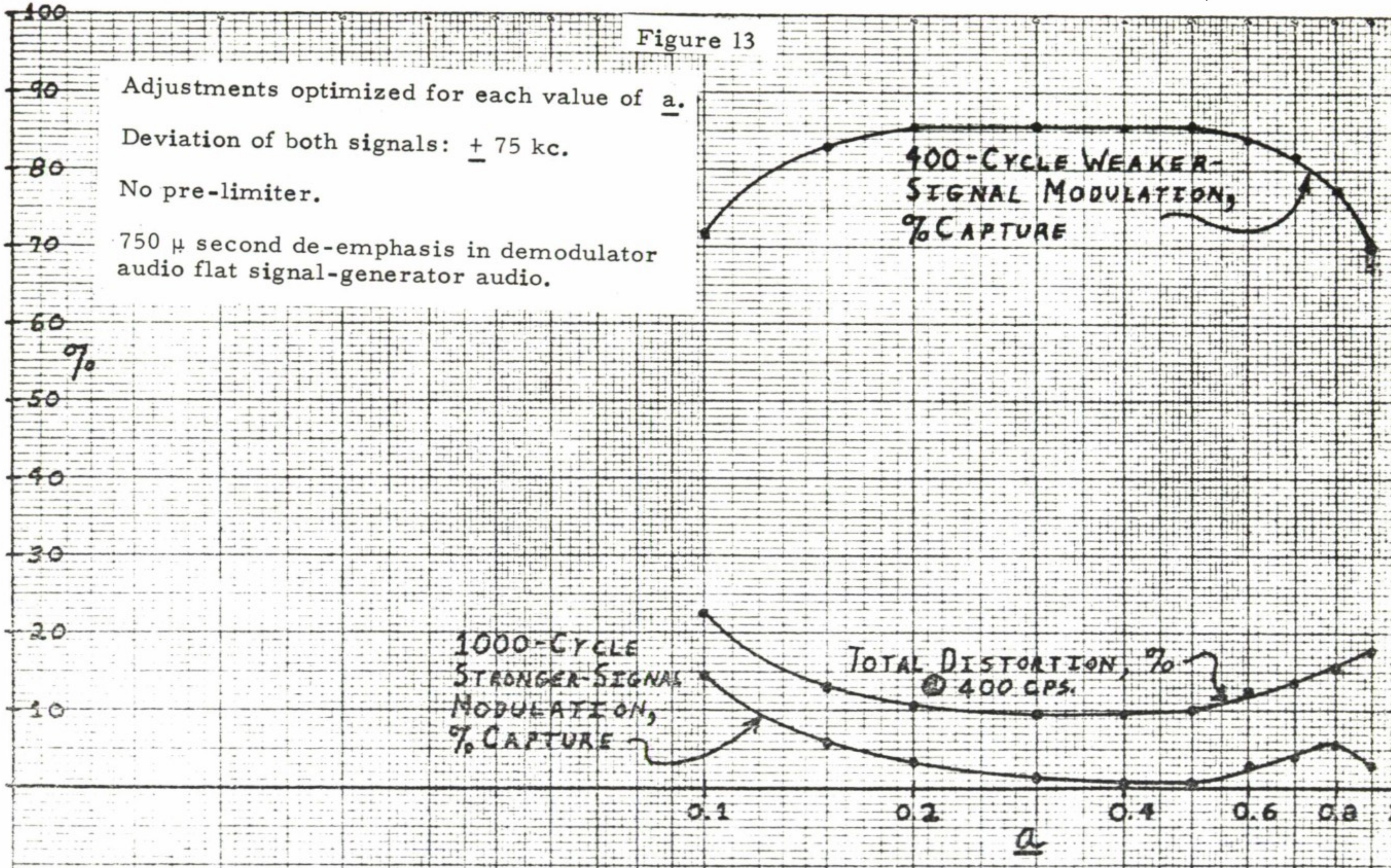


Figure 12

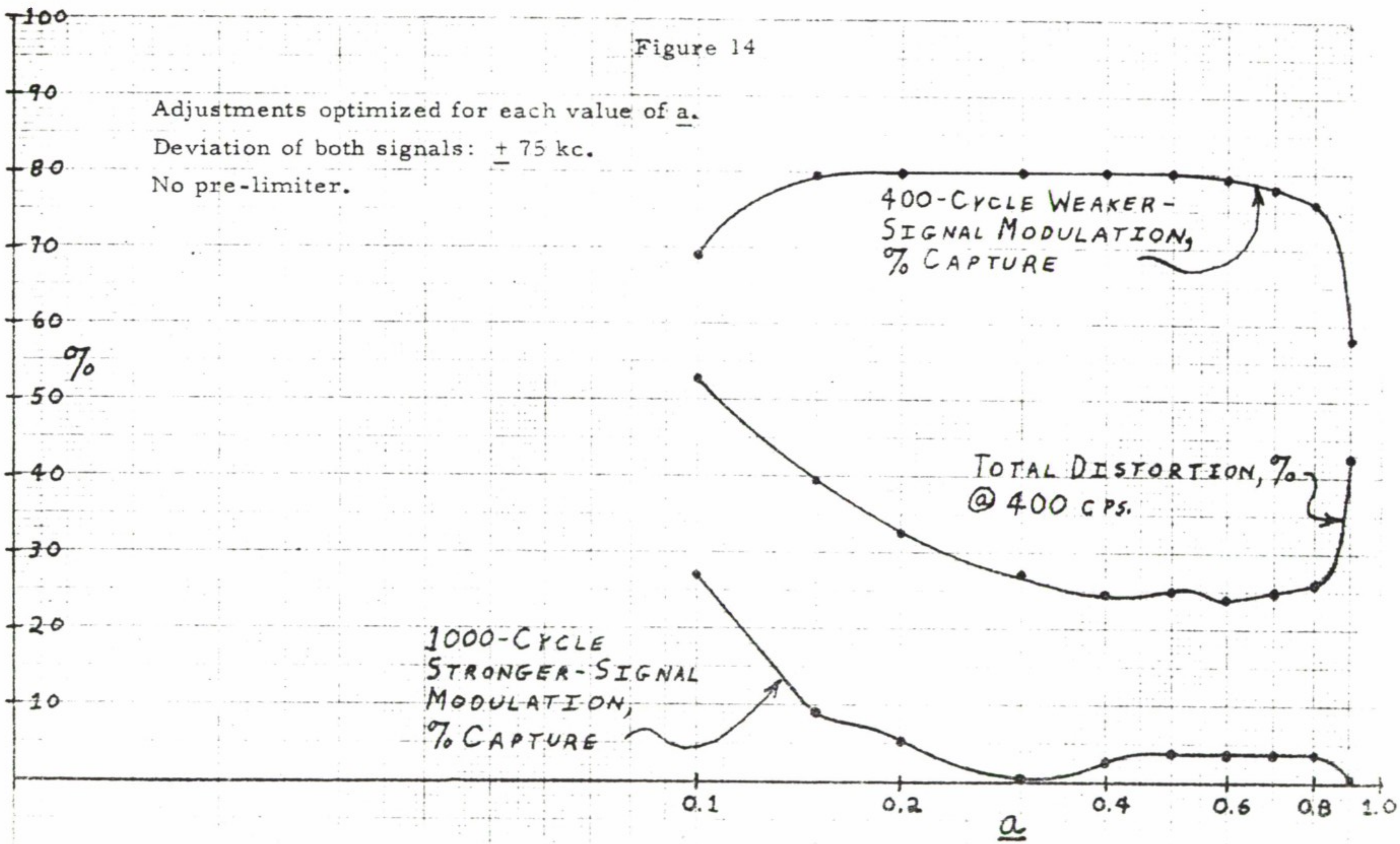
Weaker-Signal Capture Performance Initially Obtained from Transformer-Output Feedforward

Figure 13



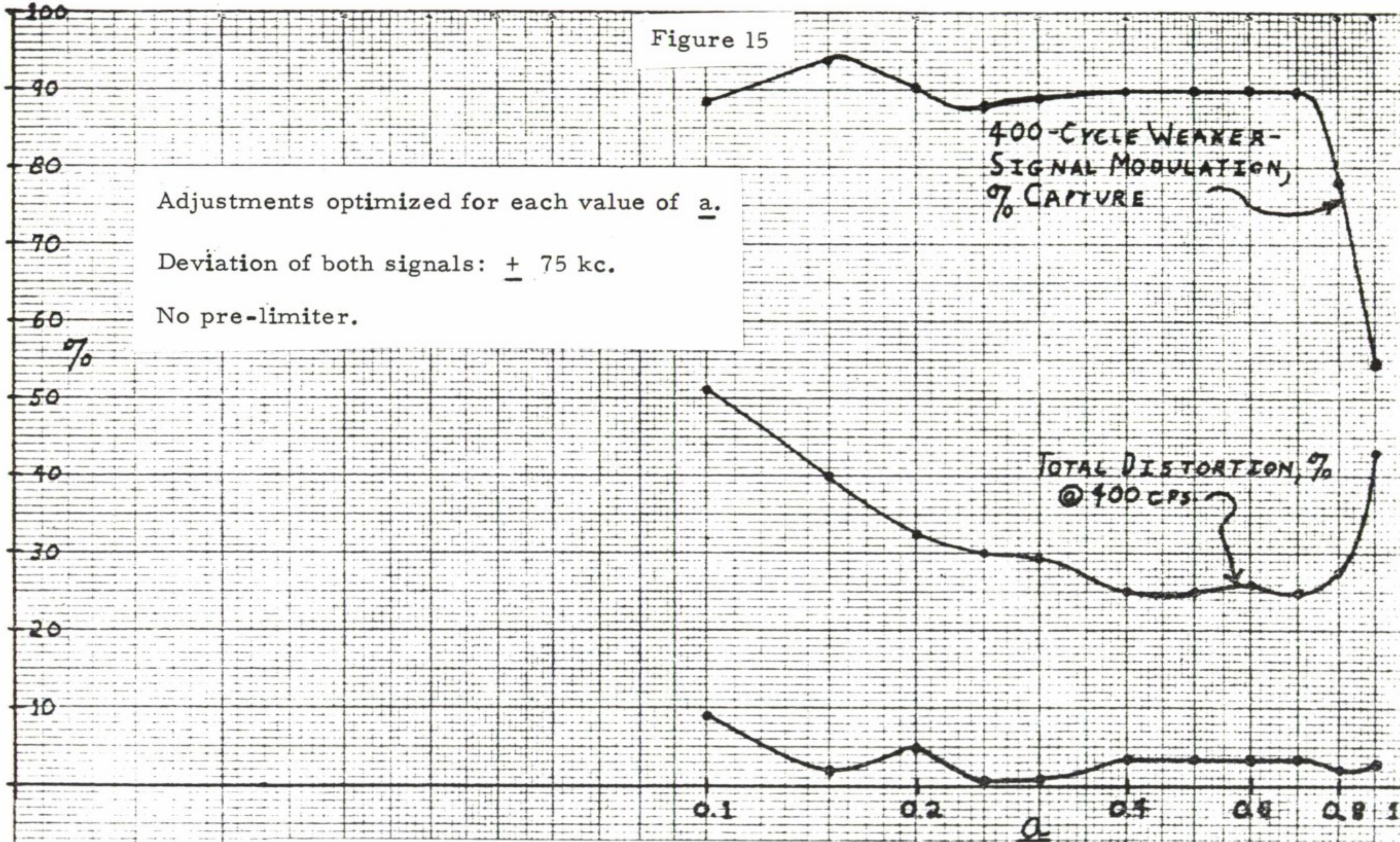
Improved Performance of Transformer-Output Feedforward After More Careful Alignment

Figure 14



Performance of Transformer-Output Feedforward with Bandpass Speech Filter in the Demodulator Audio

Figure 15



Improved Transformer-Output Feedforward Performance with Bandpass Speech Filter and Better Alignment they show slightly improved performance due to more precise alignment. All of the capture plots shown for the transformer output feedforward were obtained by optimizing adjustments at each value of a. No pre-limiter was used.

The Driver Limiter Feedforward

The feedforward circuit of Figure 14, Chapter 4, was found capable of better over-all performance than either of the other two circuits built, both in ability to capture a weaker signal at very small values of a and in amount of distortion and per cent capture in the region around a = 0.5. Hence, more extensive measurements of its performance were made than for the other two circuits. In addition to capture plots, tests were made at an a of 0.5 in which the modulating frequencies and degrees of modulation of the two signals were varied. The spectrum of the captured weaker-signal modulation and its accompanying distortion was measured under several different conditions.

Capture Plots

Figure 16 shows the capture performance obtained from the driver-limiter feedforward with and without a pre-limiter. Notice that the receiver is capable of a given per cent capture at about a 6 db lower value of a without the pre-limiter, as predicted by theory. This plot also clearly indicates that more drastic filtering than the broadcast-type 75 μ second de-emphasis is in general necessary to reduce audio distortion to tolerable levels.

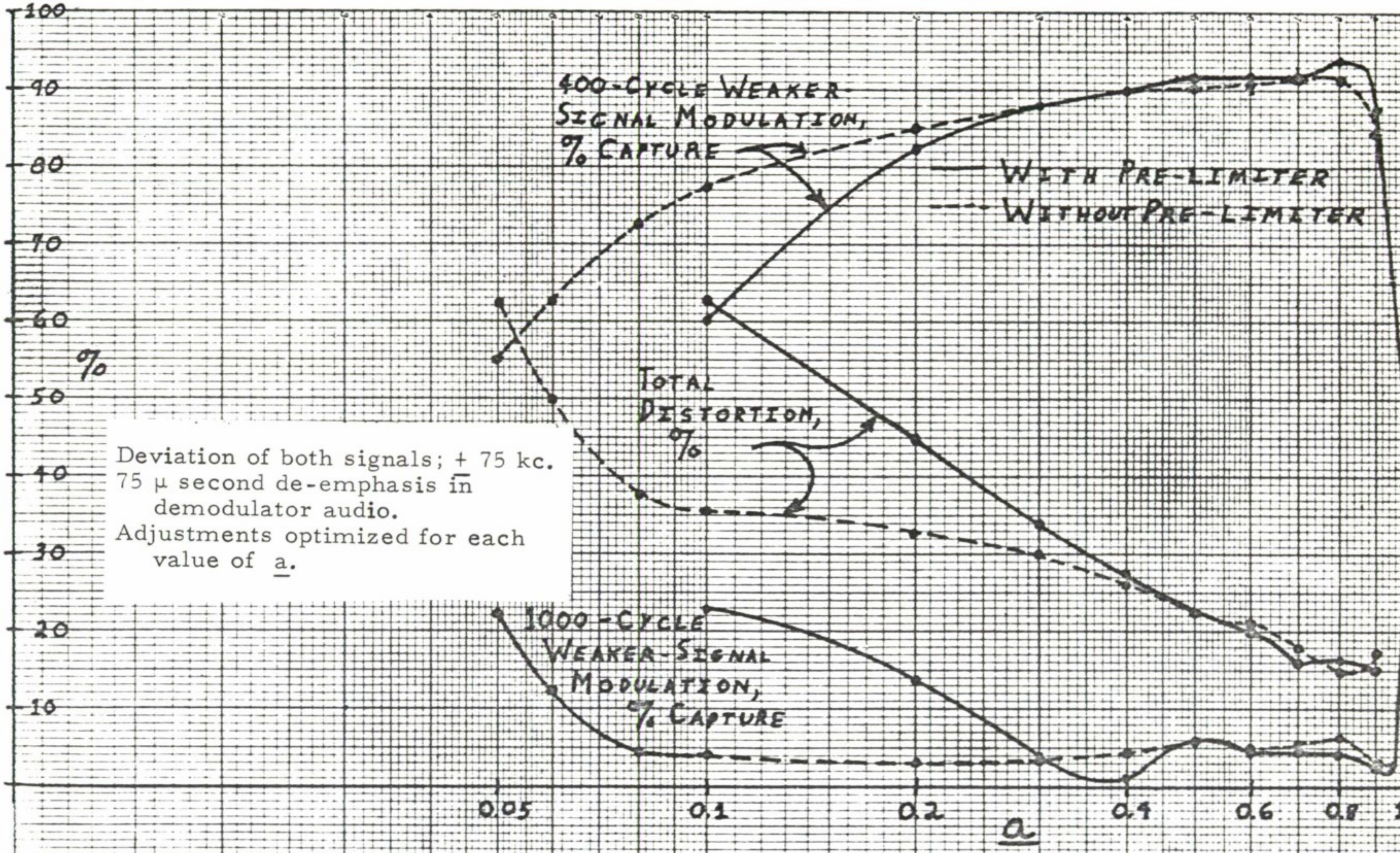


Figure 16 Weaker-Signal Capture Performance of Driver-Limiter Feedforward With and Without Pre-Limiter.

Figure 17 shows the best over-all performance obtained from any feedforward receiver to date. Note that capture of the weaker-signal modulation is better than 80% over the range $0.06 < \underline{a} < 0.9$ and that the residual stronger-signal modulation is less than 3% over most of this range and never more than 5%. Total distortion is, of course, rather low because of the heavy de-emphasis used; judging by the results of measurements on the transformer-output feedforward, values of distortion would probably range between 20% and 30% over the range of 80% capture with the more realistic bandpass speech filter in the audio system in place of de-emphasis. Figure 18 shows the appearance of the captured weaker-signal modulation waveform at an $\underline{a}$ of 0.05.

It is important to interpret Figure 17 correctly. It does not represent the performance of an operational receiver, since a number of adjustments had to be carefully optimized at each value of $\underline{a}$ to obtain the performance shown. The plot does indicate something of the potential performance of which the feedforward technique is capable at each value of $\underline{a}$. In order to realize this performance in an operational receiver under field conditions, careful design would be necessary, as outlined in Chapter 2.

Figure 19 provides a slightly more realistic picture of how well an operational feedforward receiver might perform if equipped with a control system capable of maintaining the optimum value of K. The plot was made by varying only the value of K for different $\underline{a}$; all other adjustments remaining at some compromise value. Again, the distortion curve would probably lie closer to 25% than 10% if the bandpass filter had been used instead of the heavy de-emphasis, as explained earlier.

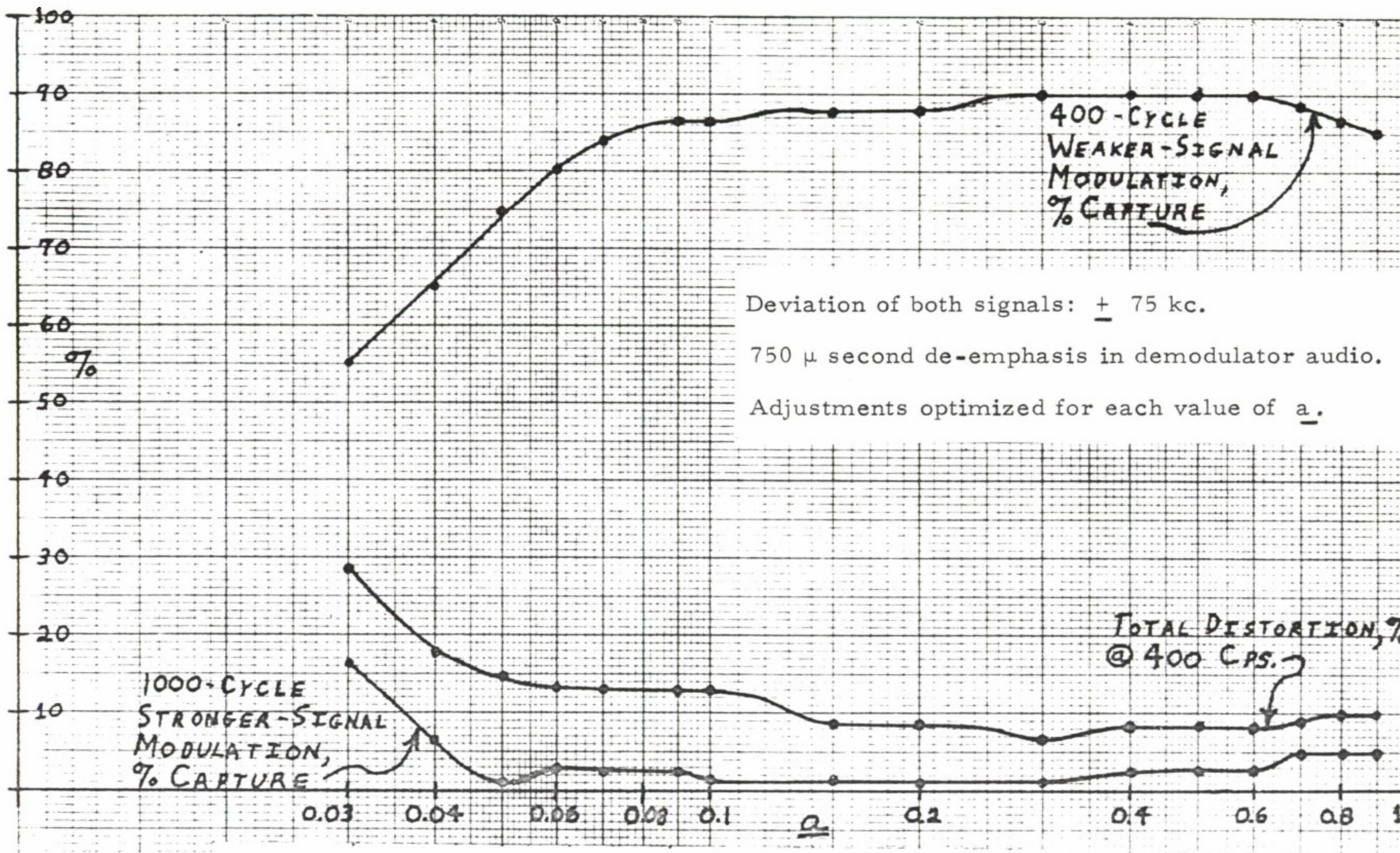
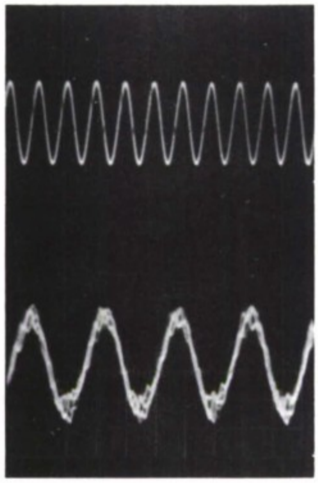
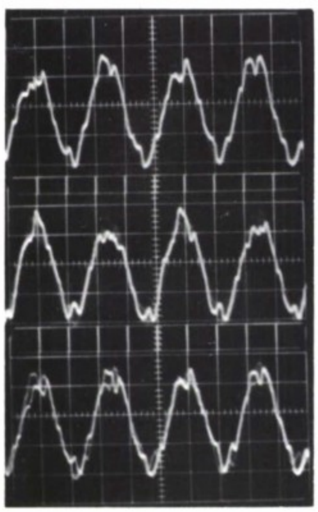


Figure 17: Best Weaker-Signal Capture Performance Obtained; Driver-Limiter Feedforward in Receiver.



K = 0. 100% capture of 1000 cycle stronger-signal modulation.

K ≈ -1. 75% capture of 400 cycle weaker-signal modulation. a = 0.05. 15% distortion with 750 μsec. de-emphasis. About 1% capture of 1000 cycle stronger-signal modulation.



Same weaker-signal modulation as above, with different scope sweep adjustment to show details of distortion.

Co-channel signals, ± 75 kc deviation. Only one adjustment (feed-forward amplifier gain) was moved between top and bottom photos.

Figure 18

Appearance of Captured Weaker-Signal Modulation Waveform, a = 0.05, For Test of Figure 17

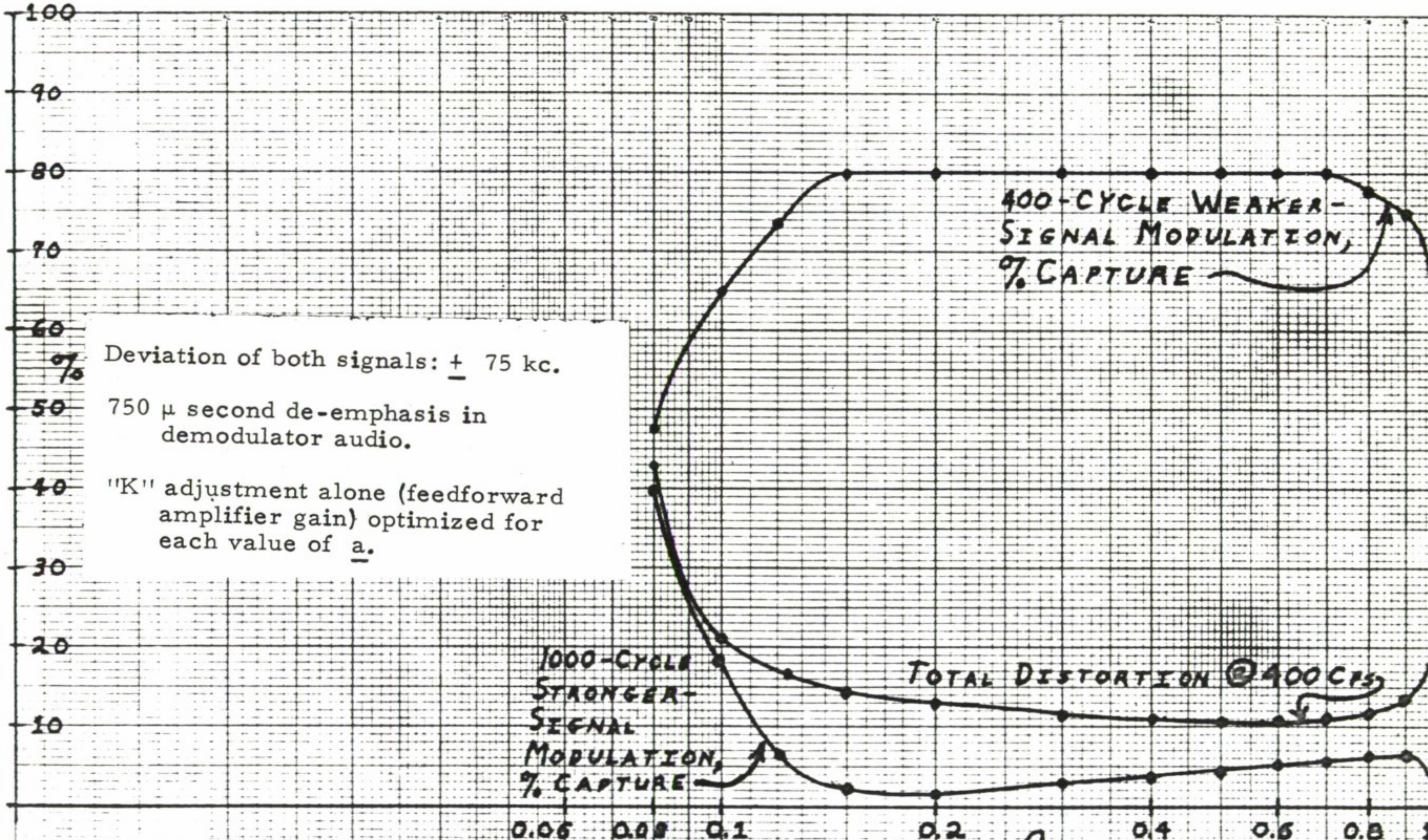


Figure 19: Weaker-Signal Capture Performance of Driver-Limiter Feedforward with K alone Adjusted for Every a.

Varying Modulation Frequencies

One of the major purposes of the experimental investigation was to determine how the weaker-signal capture performance of a feedforward receiver changed as the modulating frequencies of the two input signals were varied arbitrarily over the audio range. Accordingly, the receiver was set up with the driver-limiter feedforward and adjusted for optimum performance at an a of 0.5, a single modulating frequency being selected for the stronger signal. The frequency of the weaker-signal modulation was varied over the audio band, distortion and per cent capture being measured at a number of points. The results are plotted as Figures 20 through 29, which show per cent capture and total distortion as a function of weaker-signal modulating frequency for various conditions.

The significance of Figure 20 is explained in the introductory portion of this chapter. The results of Figures 21 through 23 were obtained with a pre-emphasis of 6 db per octave in the signal-generator audio section; the receiver audio used a 6 db/octave de-emphasis over the range 300 to 3000 cycles as well as the bandpass filter of Figure 5, Chapter 4. The distortion curves confirm the tentative conclusion derived from Figure 20: use of the standard pre-emphasis - de-emphasis technique results in excessive distortion in captured weaker-signal modulation at the higher modulating frequencies. This is rather serious for a speech channel, since the higher frequencies are known to be the most important for intelligibility.

In light of the results described above, the bandpass filter of a = 0.5

750 μ second de-emphasis in demodulator audio. Flat response in signal-generator audio.

Co-channel signals, both ± 75 kc. deviation.

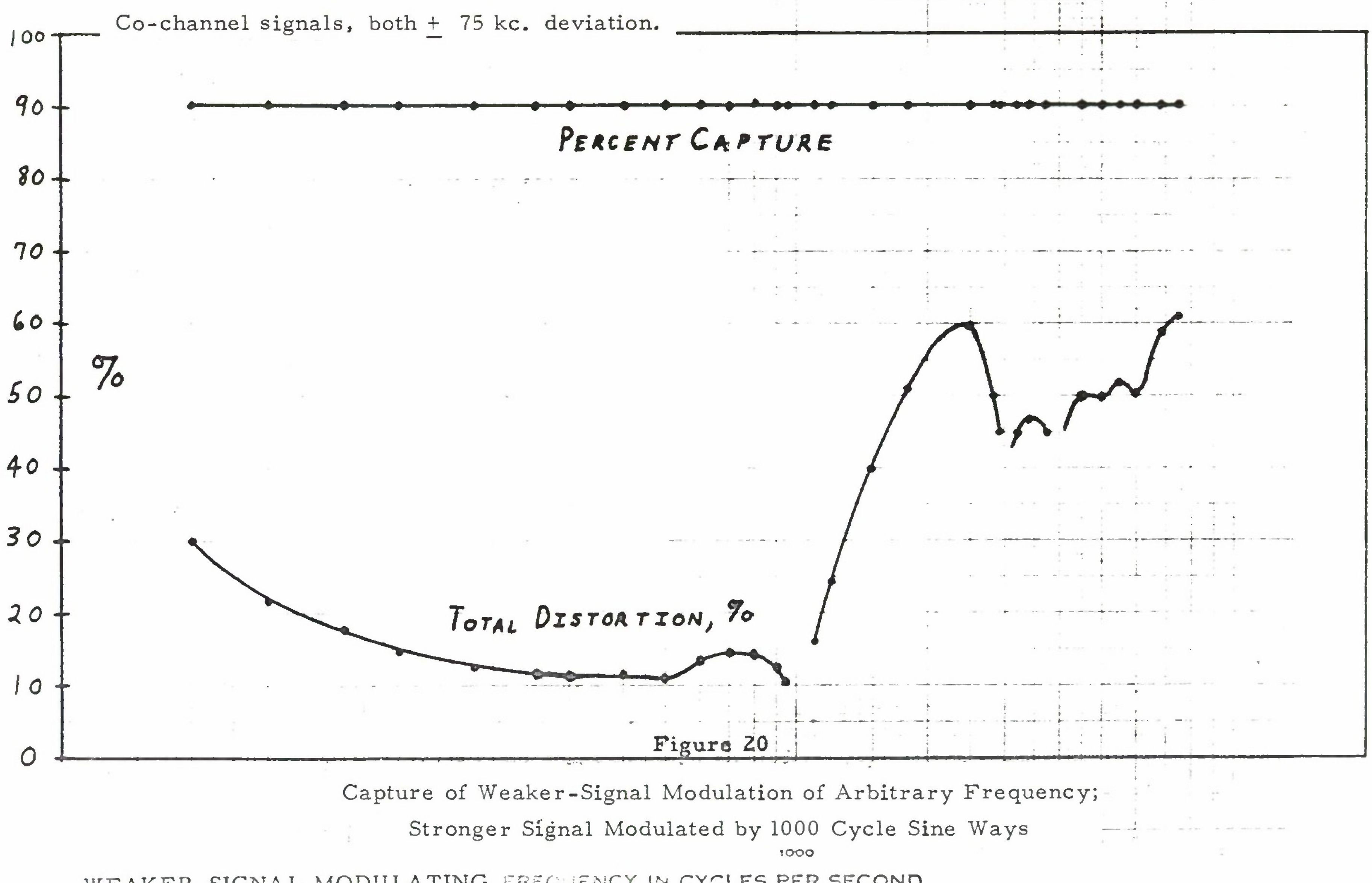


Figure 20

Capture of Weaker-Signal Modulation of Arbitrary Frequency; Stronger Signal Modulated by 1000 Cycle Sine Ways

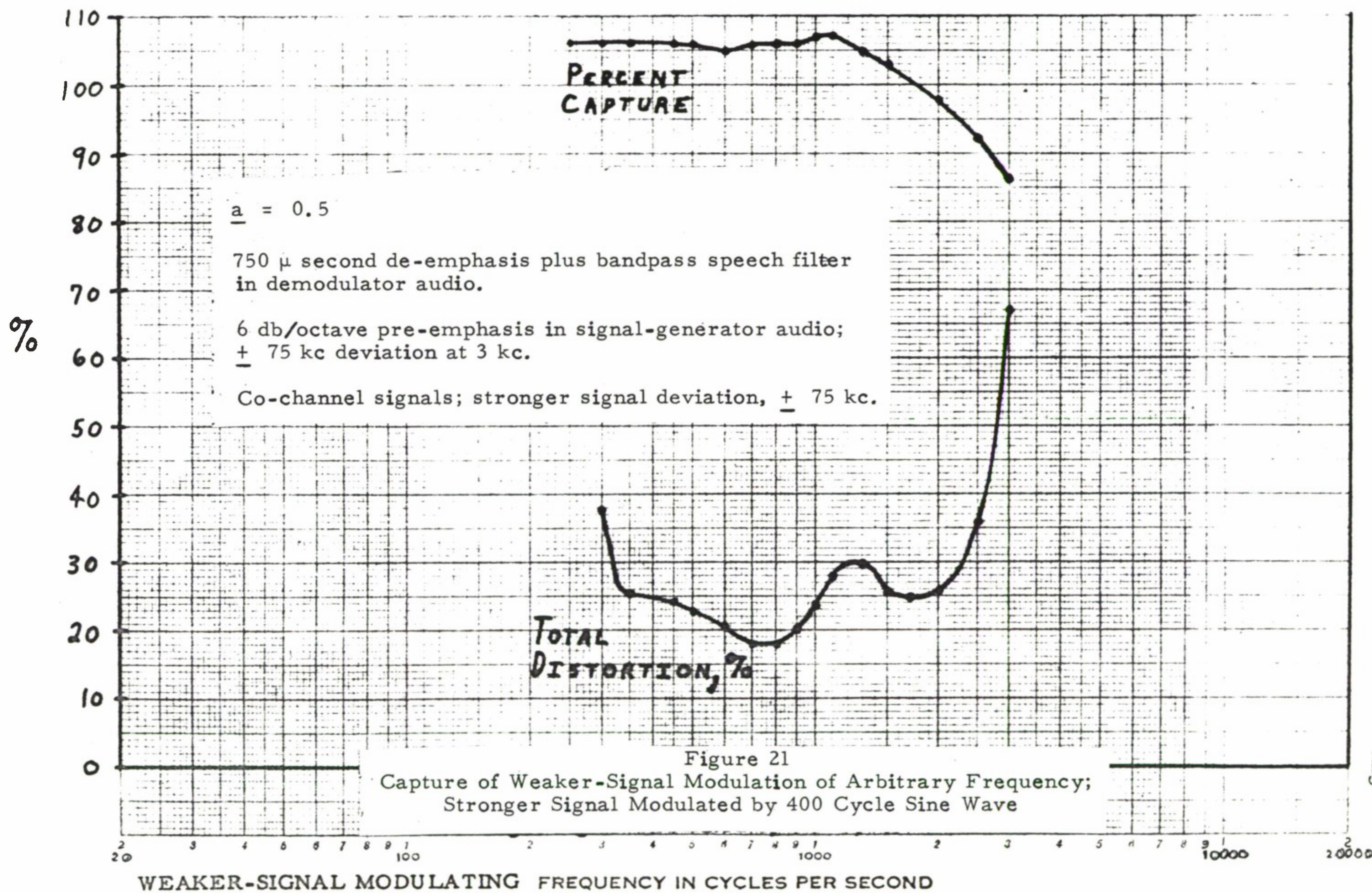
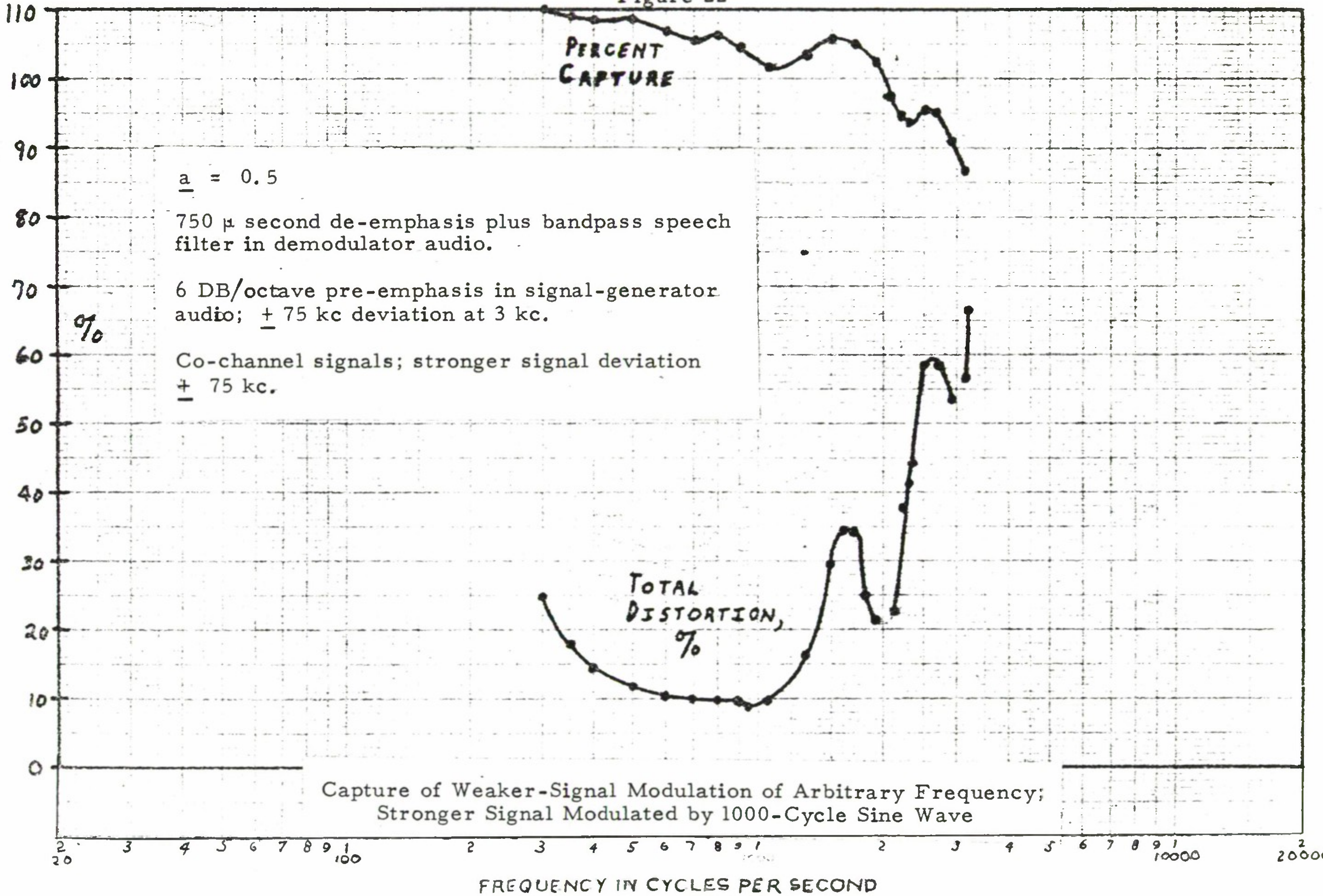


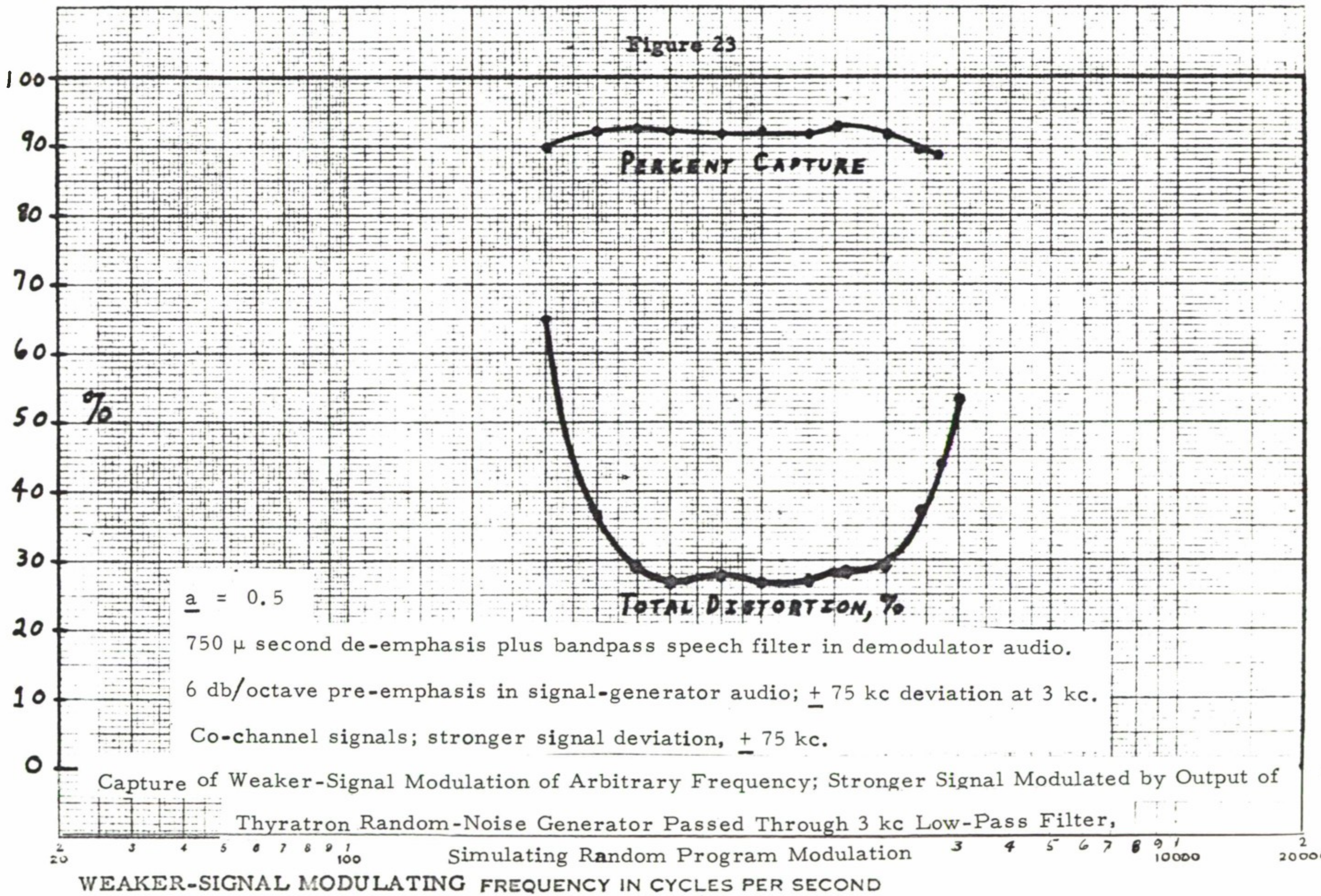
Figure 21
Capture of Weaker-Signal Modulation of Arbitrary Frequency; Stronger Signal Modulated by 400 Cycle Sine Wave

Figure 22



Capture of Weaker-Signal Modulation of Arbitrary Frequency;
Stronger Signal Modulated by 1000-Cycle Sine Wave

Figure 23



Capture of Weaker-Signal Modulation of Arbitrary Frequency; Stronger Signal Modulated by Output of Thyratron Random-Noise Generator Passed Through 3 kc Low-Pass Filter, Simulating Random Program Modulation

Figure 5, Chapter 4 was tried alone in the receiver audio, flat audio response being used in the signal generator modulator. The bandpass filter characteristic has 3 db points at 300 and 3000 cycles; this characteristic was chosen because it is the response curve generally used as a design goal for high-intelligibility speech channels. It was hoped that a receiver filter which was flat over the passband of greatest interest and fell off sharply outside would provide a better compromise for reducing audio interference which could fall anywhere in the audio spectrum than would the standard pre-emphasis - de-emphasis technique.

Use of the flat receiver audio filter with flat signal-generator audio proved as predicted to be an excellent compromise, as shown by the plots of Figures 24 through 29, all measured with the bandpass filter in the audio section of the demodulator. The plots are the same type as those of Figures 20 through 23. Each was measured with a different modulating frequency on the stronger signal. In Figure 24, the stronger signal modulating frequency is below the passband of the audio filter; in Figure 25, it is inside the lower edge; in Figure 26, it is near the geometric center of the filter passband; in Figure 27, it is at the upper edge; and in Figure 28 above the passband.

It seems safe to conclude from the figures that per cent capture is essentially independent of the weaker-signal modulating frequency for the high deviation ratio used (25). Distortion is surprisingly low when the stronger-signal modulating frequency is just inside the upper edge of the audio filter passband or above the passband altogether. When the stronger-signal modulating frequency is within or below the filter

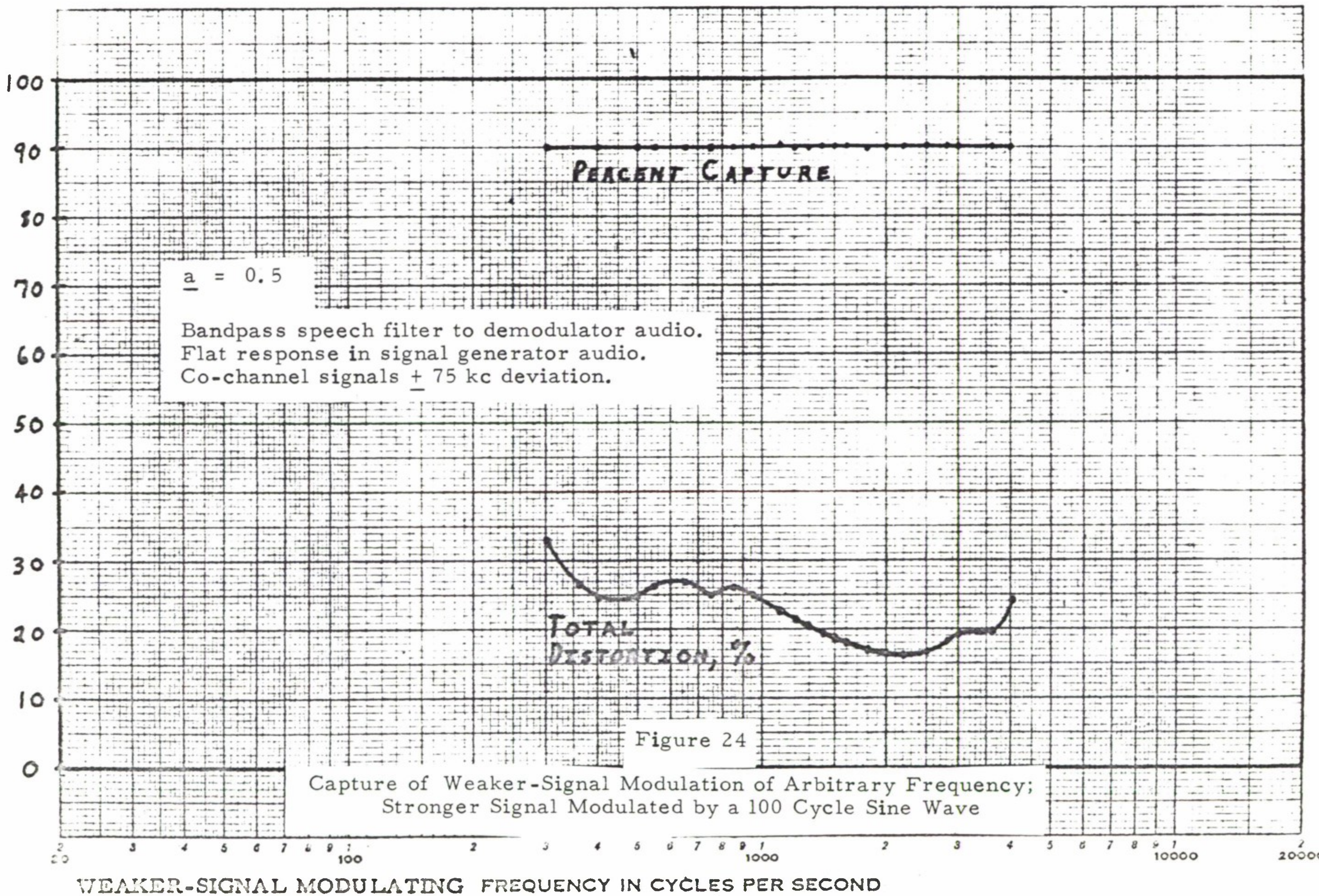


Figure 24

Capture of Weaker-Signal Modulation of Arbitrary Frequency; Stronger Signal Modulated by a 100 Cycle Sine Wave

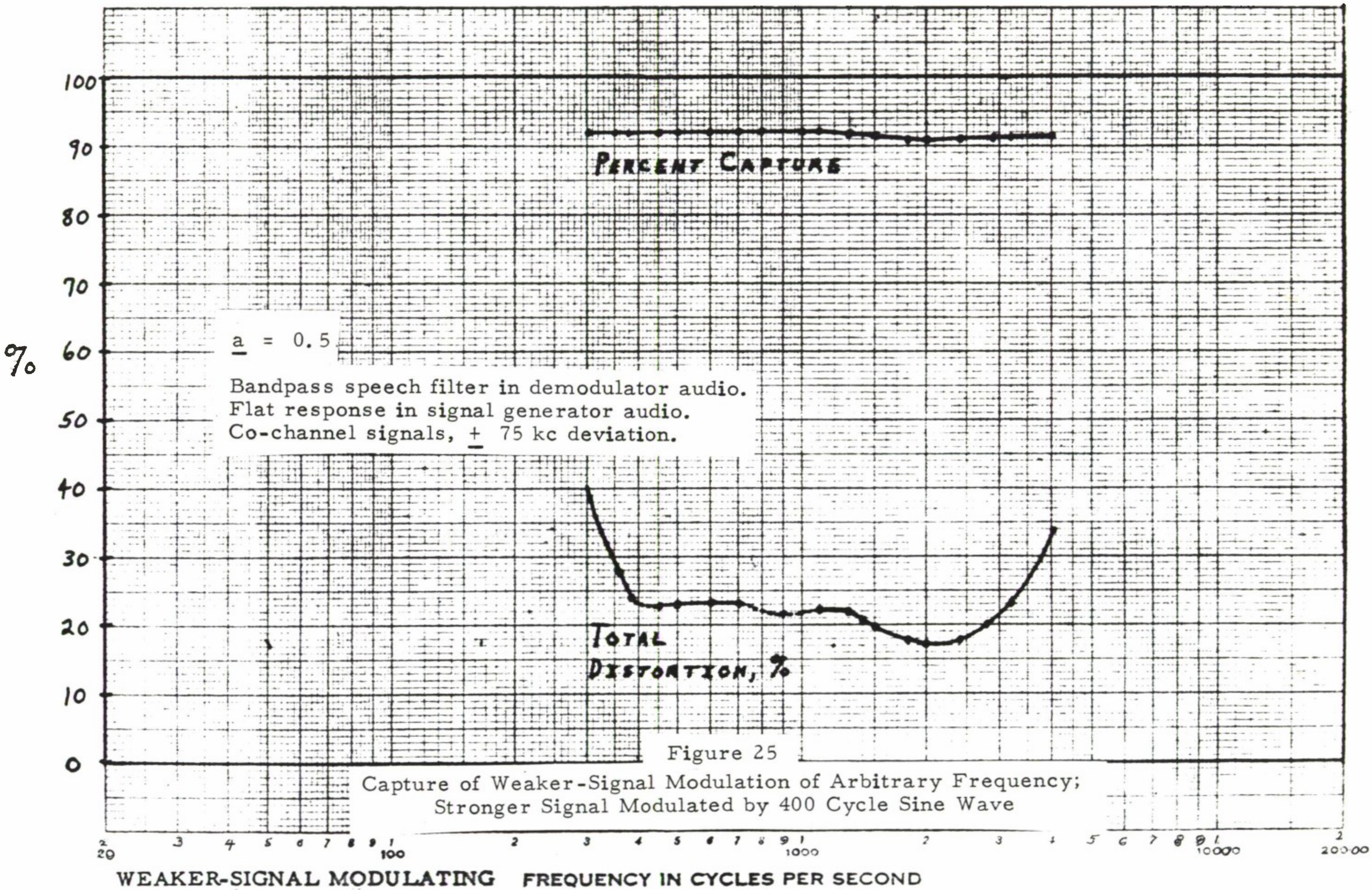


Figure 25

Capture of Weaker-Signal Modulation of Arbitrary Frequency; Stronger Signal Modulated by 400 Cycle Sine Wave

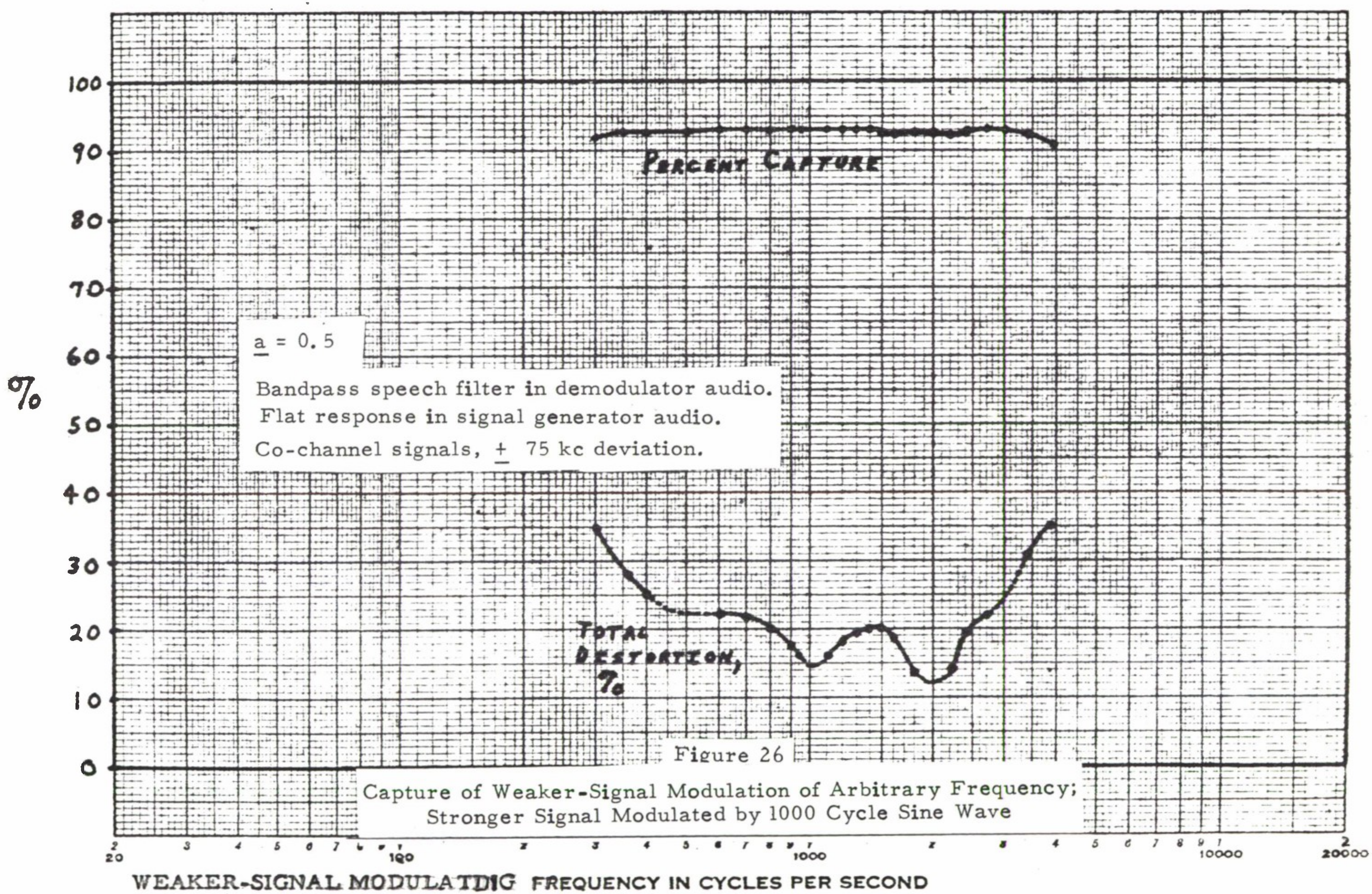


Figure 26

Capture of Weaker-Signal Modulation of Arbitrary Frequency; Stronger Signal Modulated by 1000 Cycle Sine Wave

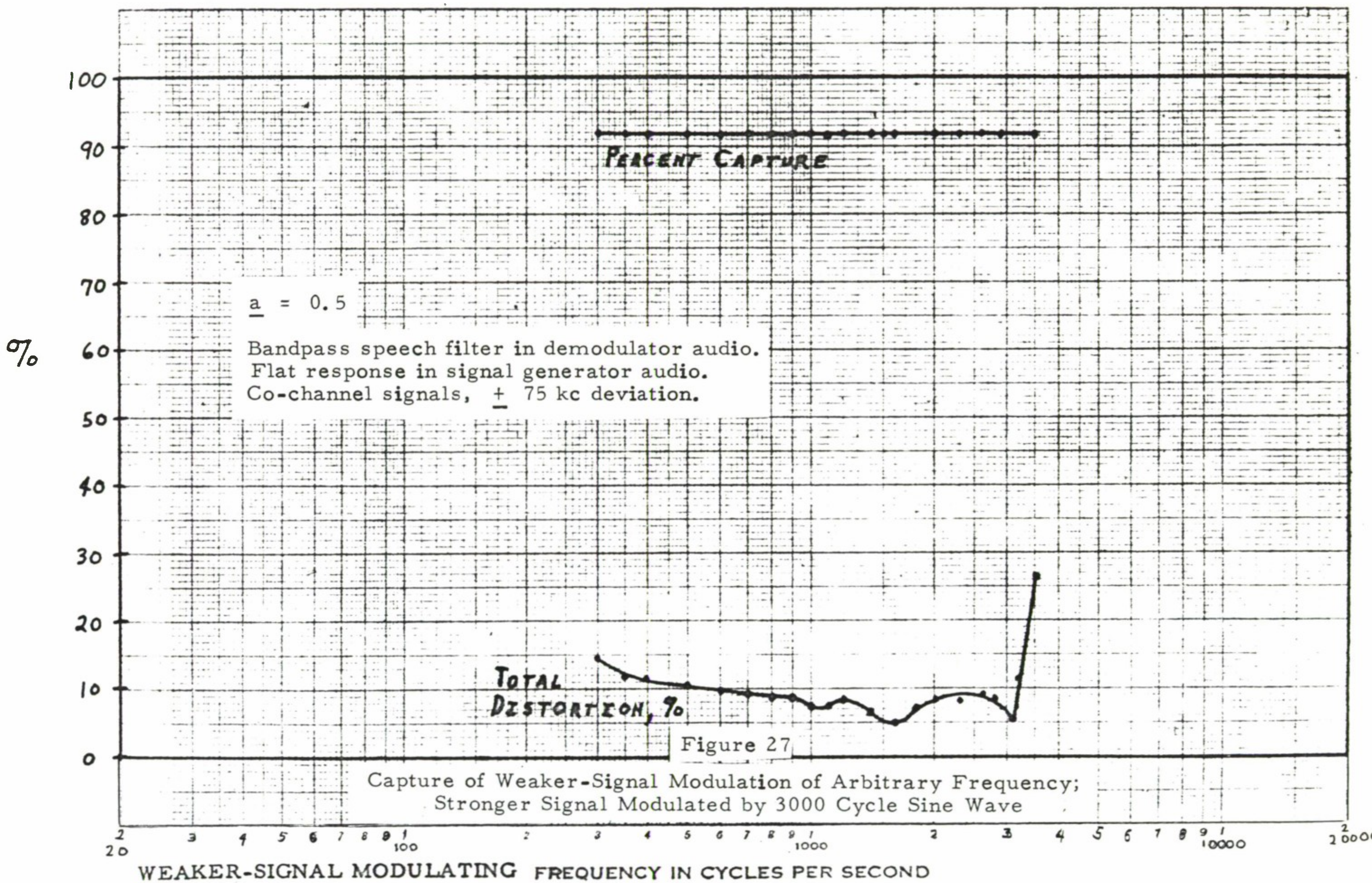


Figure 27

Capture of Weaker-Signal Modulation of Arbitrary Frequency;
Stronger Signal Modulated by 3000 Cycle Sine Wave

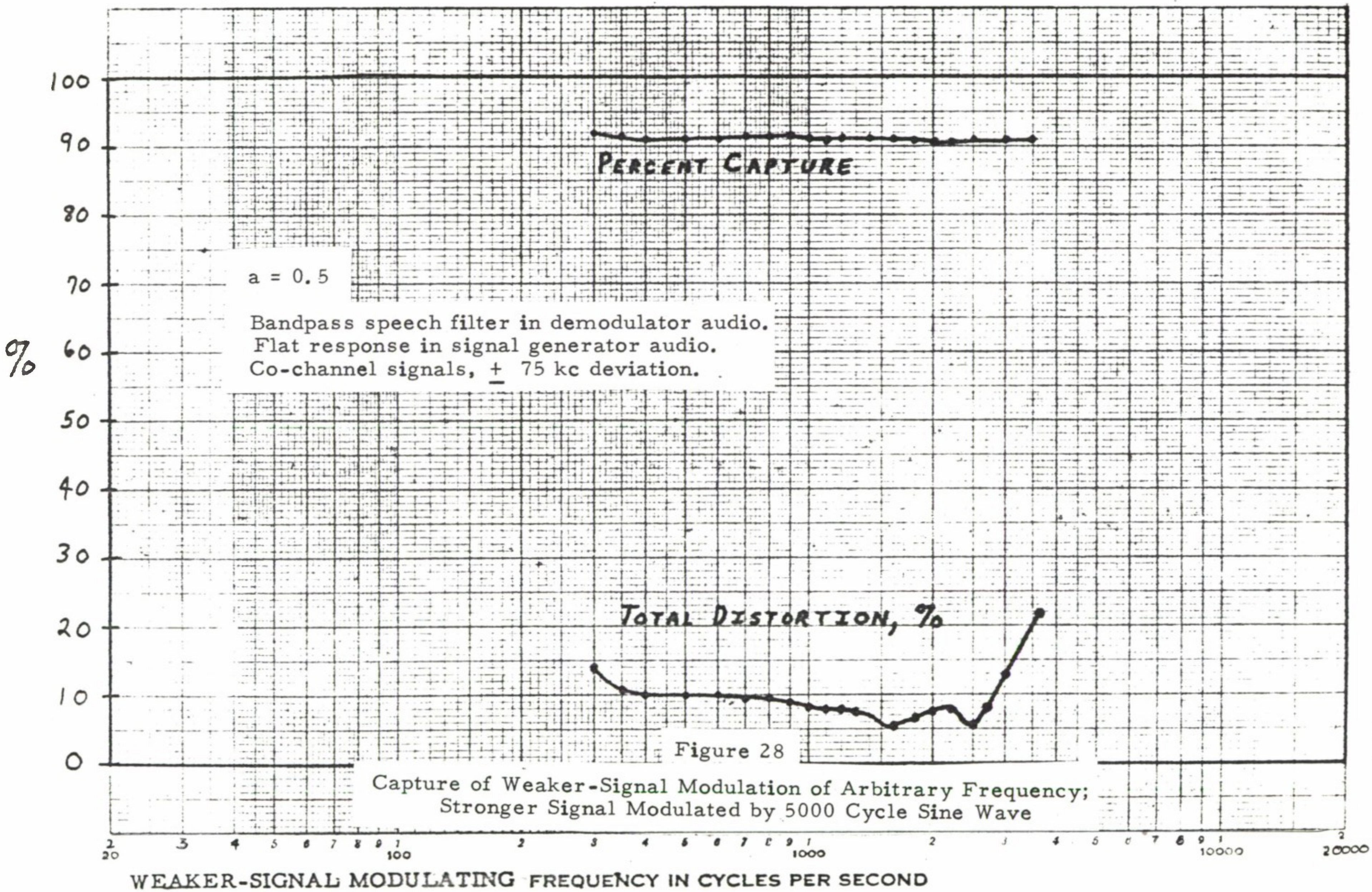


Figure 28

Capture of Weaker-Signal Modulation of Arbitrary Frequency; Stronger Signal Modulated by 5000 Cycle Sine Wave

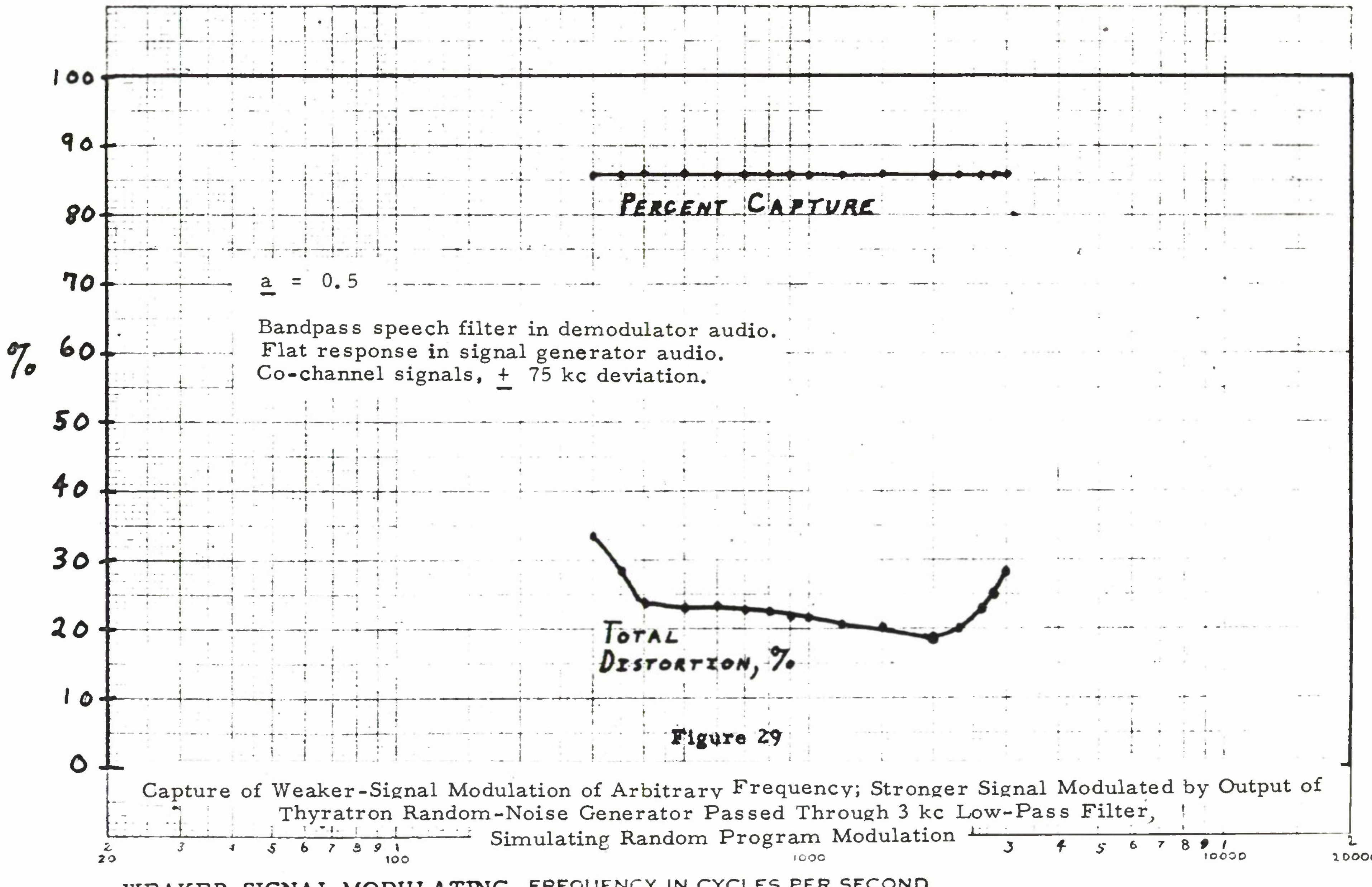


Figure 29

Capture of Weaker-Signal Modulation of Arbitrary Frequency; Stronger Signal Modulated by Output of Thyratron Random-Noise Generator Passed Through 3 kc Low-Pass Filter, Simulating Random Program Modulation passband, the distortion level should allow fair but not good quality speech transmission on the weaker signal. In all cases, distortion rises rapidly when the weaker-signal modulating frequency begins to move out of the filter passband because the modulation is then attenuated with respect to the distortion within the passband.

Spectrum of Captured Weaker-Signal Modulation

The spectrum of the inherent distortion involved in weaker-signal capture seems to follow a simple rule when the modulation on both weaker and stronger signals is sinusoidal: components appear at frequencies that equal the highest common factor of the two modulating frequencies and all of its harmonics. For example, if the stronger signal is modulated by a 1000 cps signal and the weaker by a 300 cps signal, the distortion accompanying the recovered weaker-signal modulation will have components at 100 cycles and all of its harmonics, since 100 is the highest common factor of 300 and 1000. An actual spectrum measured for this case is shown in Figure 30. The strongest components are those corresponding to lower-order interaction, such as 1000 $\pm$ 300 cycles and 2(1000) $\pm$ 300 cycles. The interaction between signals does seem to be of a fairly high order, however, since all of the harmonics of the 100 cycle HCF frequency are measurable up to 5 kc and beyond. Physically, 100 cycles is basic repetition frequency of the interference pattern of the 300 cycle and 1000 cycle sine waves. Distortion is produced whenever the two FM signals cross in frequency, and the pattern of the frequency crossings repeats at a

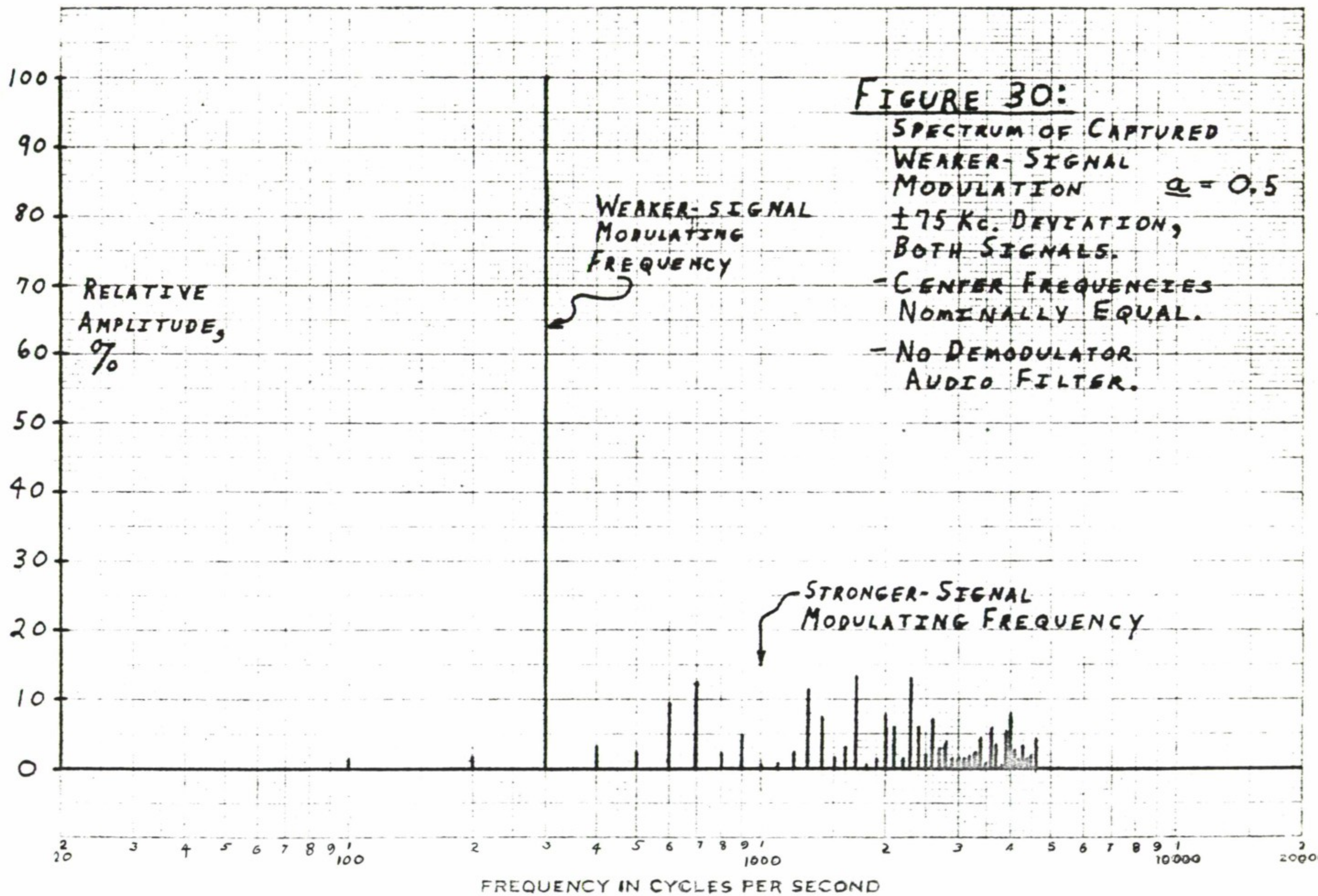


FIGURE 30: SPECTRUM OF CAPTURED WEAKER-SIGNAL MODULATION $\underline{a} = 0.5$
±75 Kc. DEVIATION, BOTH SIGNALS.
- CENTER FREQUENCIES NOMINALLY EQUAL.
- NO DEMODULATOR AUDIO FILTER.

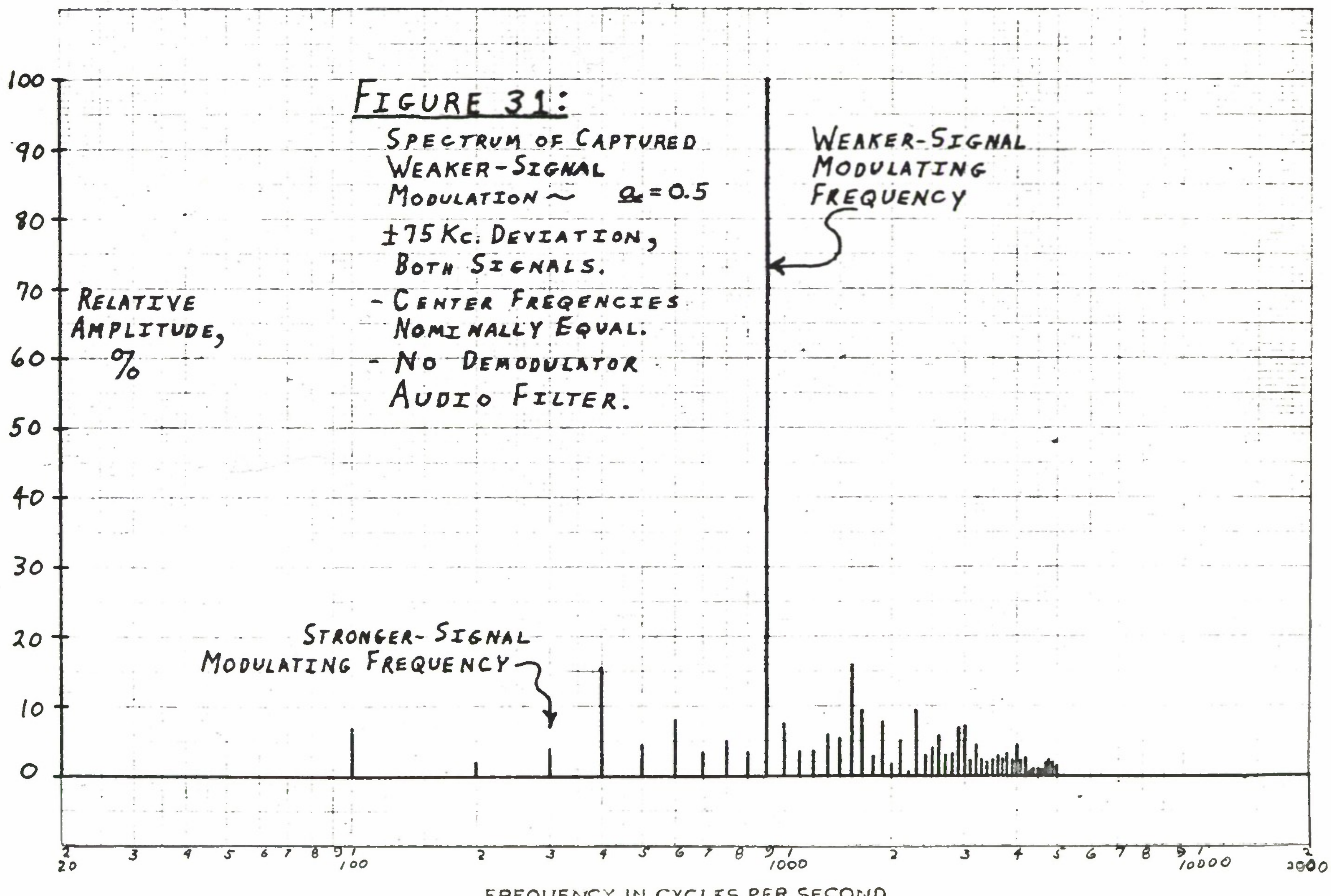


FIGURE 31: SPECTRUM OF CAPTURED WEAKER-SIGNAL MODULATION ~ $a = 0.5$

±75 Kc. DEVIATION, BOTH SIGNALS.

- CENTER FREQUENCIES NOMINALLY EQUAL.
- NO DEMODULATOR AUDIO FILTER.

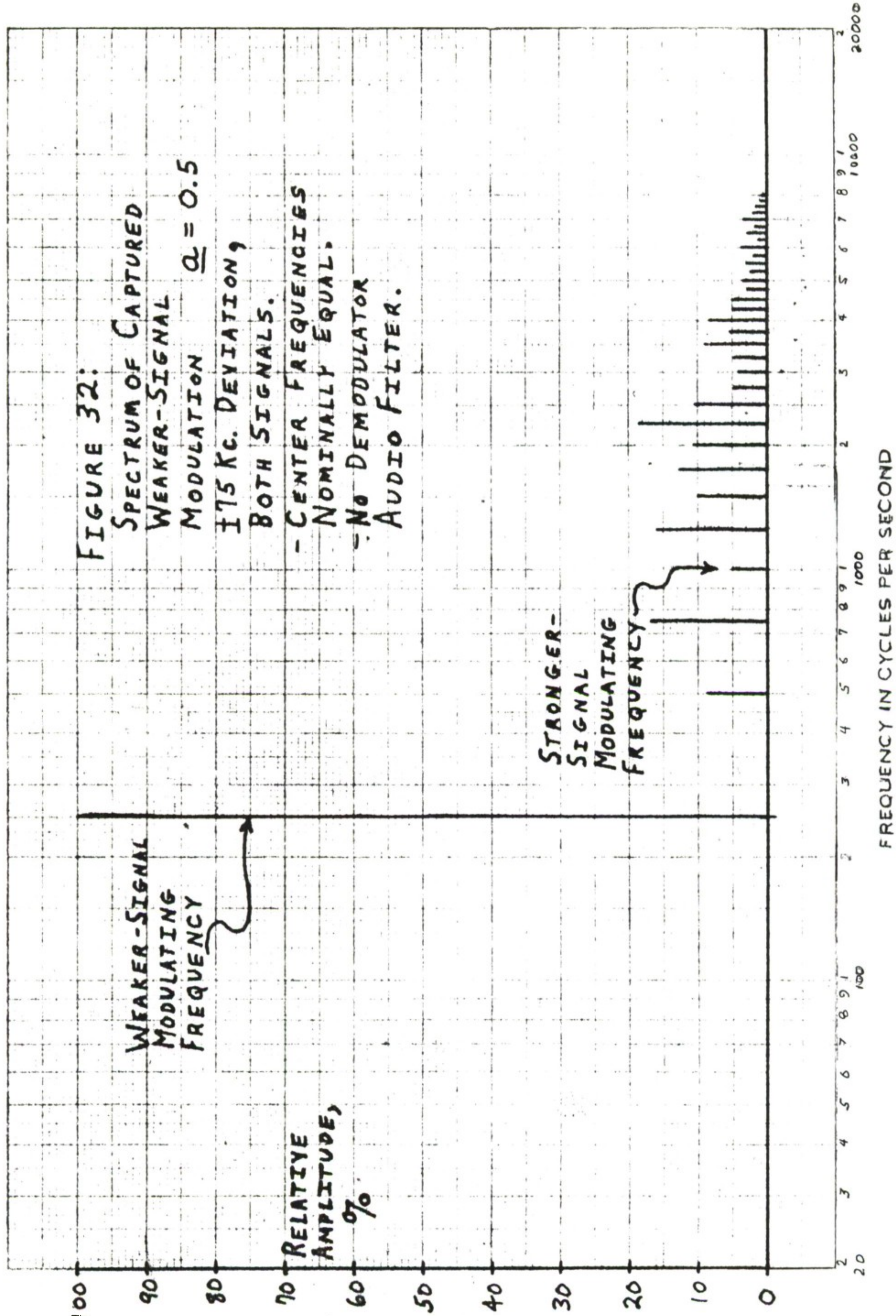


FIGURE 32:
SPECTRUM OF CAPTURED
WEAKER-SIGNAL
MODULATION a = 0.5
±75 KC. DEVIATION,
BOTH SIGNALS.
- CENTER FREQUENCIES
NOMINALLY EQUAL.
- NO DEMODULATOR
AUDIO FILTER.
WEAKER-SIGNAL
MODULATING
FREQUENCY
STRONGER-
SIGNAL
MODULATING
FREQUENCY
RELATIVE
AMPLITUDE,
%
100
90
80
70
60
50
40
30
20
10
0
20
100
1000
10000
20000
FREQUENCY IN CYCLES PER SECOND

100 cycle rate, producing the 100 cycle fundamental and its harmonics in the demodulator output.

Figures 31 and 32 are further examples of the spectrum of weaker-signal modulation plus distortion. Note the clear predominance of the weaker-signal modulation component, the relative unimportance of the fundamental stronger-signal modulating frequency compared to other interference components, and the adherence of the component frequencies to the "highest common factor" rule.

Reduced Deviation Tests

Tests were conducted at an a of 0.5 with fixed modulating frequencies on both signals to determine how weaker-signal capture performance would be affected by reducing the frequency deviation on each signal.

Figure 33 shows the effect of reducing the deviation of the weaker signal, stronger-signal deviation remaining at the full ± 75 kc. Note that distortion decreases with deviation down to a point, then increases rapidly. The per cent capture is actually greater than 100% for small weaker-signal deviations; this means that the fundamental weaker-signal modulation component at the demodulator output is stronger in the presence of interference. The reason for this effect is not known, nor was any reason found for the dip in the per cent capture curve with 400 cycle modulation on the stronger signal.

Figure 34 indicates that some improvement in distortion can be obtained by readjusting the feedforward for smaller values of weaker-signal deviation.

The effects of reduced stronger-signal deviation are shown in Figures 35 and 36. Note that performance deteriorates significantly for reduced deviation, then improves for very small values of stronger-signal deviation. Also, a significant improvement in performance is obtainable at small values of deviation by careful adjustment. These facts seem to suggest that the feedforward circuit can reject unmodulated or low-deviation signals but that it works in a somewhat different way than for fully-modulated interference.

Speech Intelligibility Tests

A few brief tests were conducted to obtain a subjective evaluation of the quality and degree of intelligibility of speech modulation recovered from the weaker of two co-channel signals. The stronger co-channel signal was modulated successively at 100, 400, 1000, and 5000 cycles; deviation was varied from zero up to the full 75 kc. The weaker co-channel signal ($\underline{a}$ = 0.5) was modulated with a voice signal from a microphone, and the output of the feedforward receiver was recorded on an ordinary tape recorder for later evaluation by ear. Some tests were conducted using a speech clipper and low-pass filter in the signal-generator speech modulator. The bandpass speech filter was, of course, used in the receiver audio section.

The speech recorded on the tape by the method just described was surprisingly intelligible. There was, as expected, background noise consisting of a complex audio tone whose amplitude and quality varied with the voice modulation; it was generally loudest in the absence of voice modulation. As might be predicted from the distortion plots,

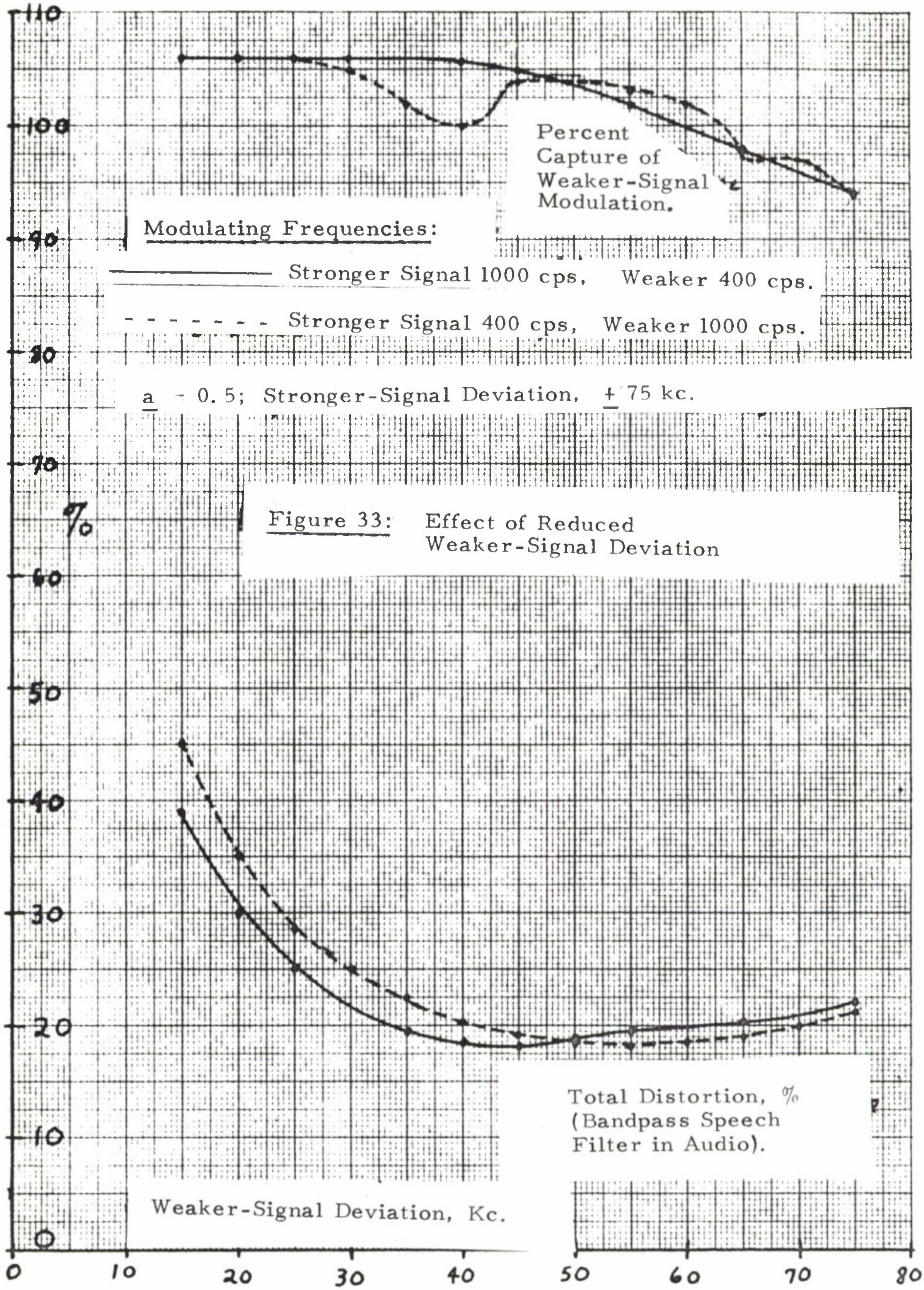


Figure 33: Effect of Reduced Weaker-Signal Deviation

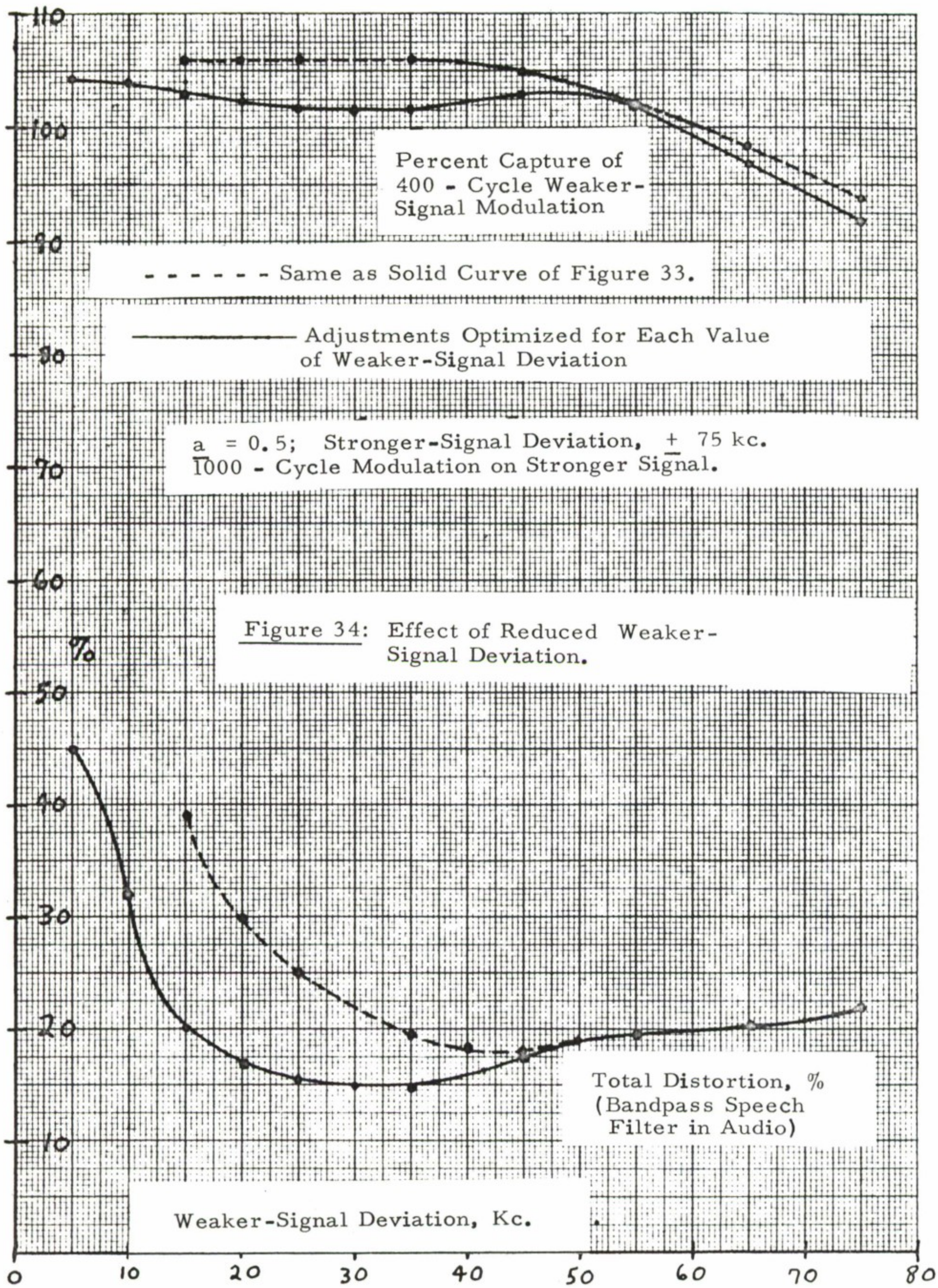


Figure 34: Effect of Reduced Weaker-Signal Deviation.

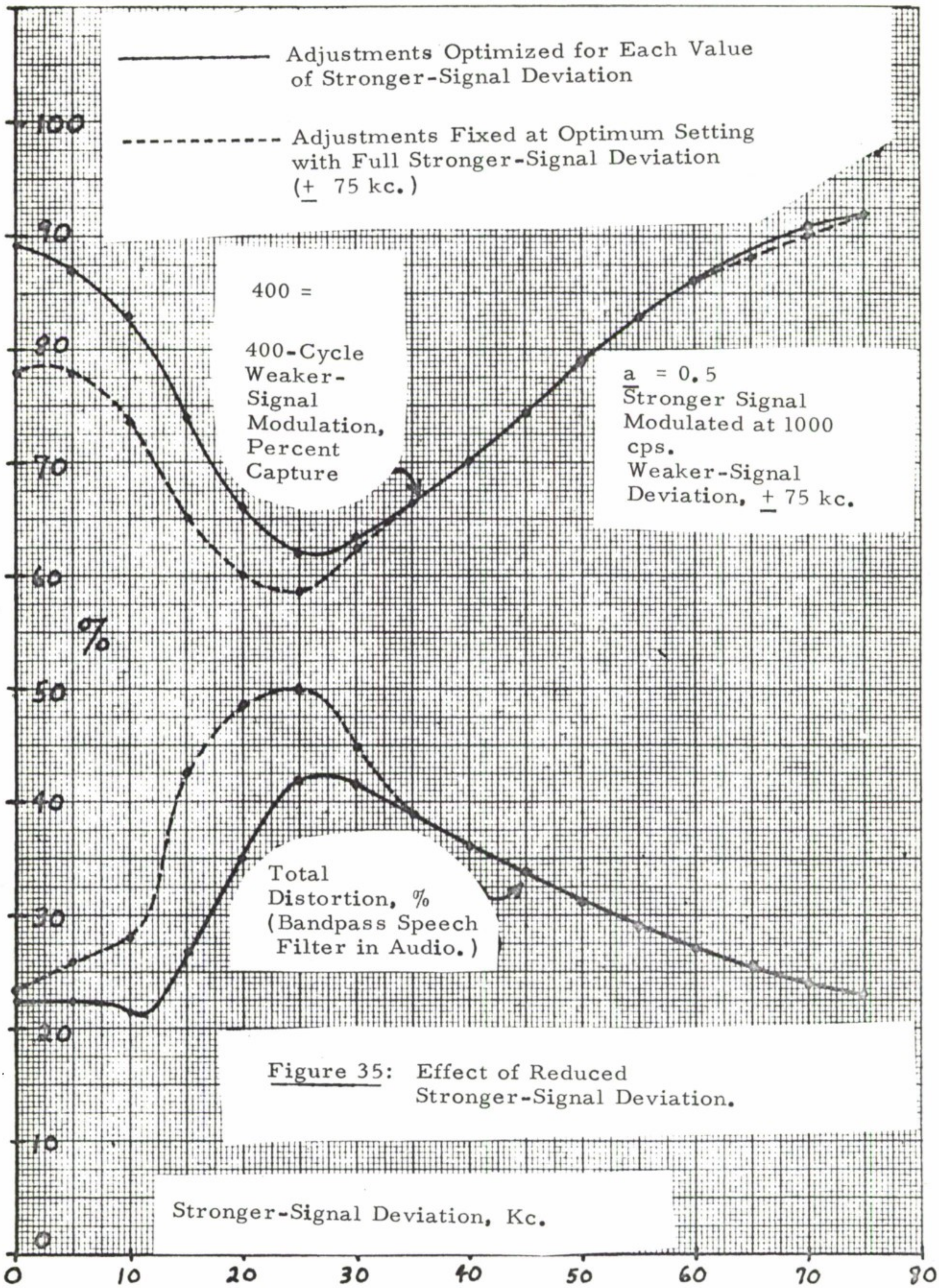


Figure 35: Effect of Reduced Stronger-Signal Deviation.

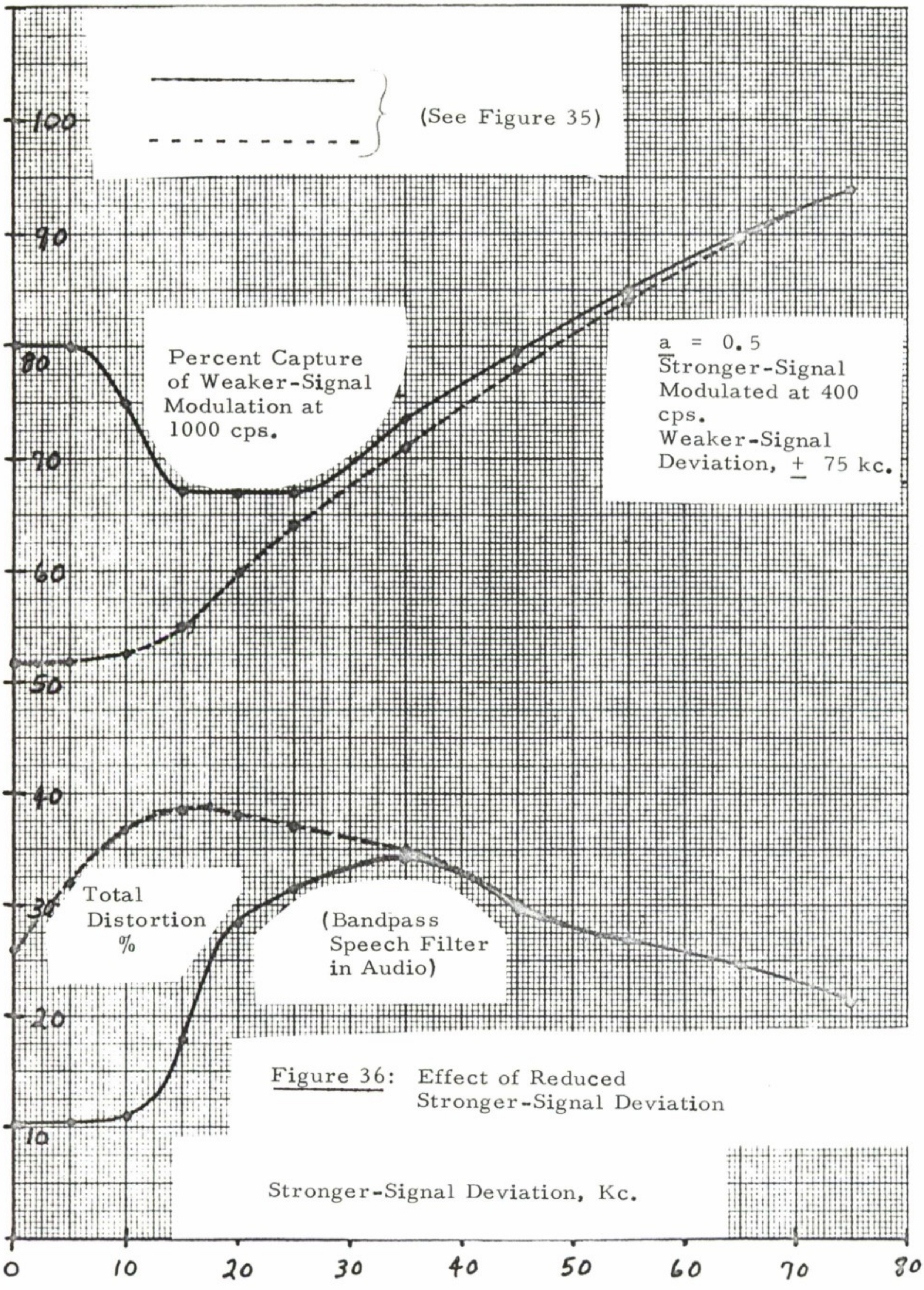


Figure 36: Effect of Reduced Stronger-Signal Deviation

speech quality was excellent with 5000 cycle modulation on the stronger signal; the background noise was more like a hiss than a tone. For other modulating frequencies on the stronger signal, there was noticeable distortion of the speech when compared with speech transmitted over the same system without interference. The speech quality was surprisingly good for low stronger-signal deviations and even with an unmodulated stronger signal; this was somewhat unexpected, considering the results of the quantitative distortion measurements with reduced stronger-signal deviation.

The use of speech clipping and filtering in the signal-generator speech modulator produced pretty much the expected results: the recovered speech sounded fuller and more powerful but less natural. The clipping seemed to help somewhat against the background interference, but the difference was not very great.

In a situation in which both the desired weaker signal and the interfering stronger co-channel signal have the same nominal peak deviation and the stronger signal is fully modulated, as in the test, the reduction in distortion of captured weaker-signal modulation for reduced weaker-signal deviation acts to favor speech modulation. Since a speech waveform consists of high peaks with a generally lower average level (R.M.S. value approximately 1/3 peak value), the deviation of the speech-modulated weaker-signal transmitter is less than its maximum value a sizable percentage of the time, resulting in reduced distortion.

In summary, the recovered voice modulation is probably best described as usable, fully intelligible speech of fair but not particularly good quality.

CHAPTER 6

SUMMARY AND CONCLUSIONS

The feedforward technique can be used to enhance the performance of an FM receiver in rejecting interference either weaker or stronger than a desired signal. Its usefulness in stronger-signal capture must be examined in a given circumstance in the light of alternative stronger-signal capture techniques. Feedforward can deliver excellent performance, but the improvement in performance over an alternate technique of comparable complexity may not be worth the additional design problems that go with feedforward. However, the flexibility and conceptual simplicity of feedforward may be quite attractive in particular stronger-signal capture applications, especially in a receiver used by a skilled radio operator.

The problem of weaker-signal capture is both more complex and more interesting; the feedforward technique is conceptually simpler and more straightforward than any other existing weaker-signal capture technique, but its simplicity may often be offset by the close tolerances on component circuits necessary for high performance. Precision of at least $100(\underline{a}/2)$ per cent is required for $\underline{a} < 0.5$ and at least $100(1-\underline{a})$ per cent for $\underline{a} > 0.5$ for weaker-signal capture.

Three basic types of practical feedforward circuits were built as laboratory models. All demonstrated various degrees of weaker-signal capture and some improvement in stronger-signal capture. The best of these experimental results indicate that reasonably good weaker-signal capture can be achieved under laboratory conditions with a feedforward receiver for $0.06 < \underline{a} < 0.9$; this corresponds to tolerances of about 3 per cent on all important system parameters. Extension of performance to smaller values of $\underline{a}$ is dependent on attaining better than 3 per cent accuracy in bandpass filter responses, limiter characteristics, and amplifier gain over all parts of the modulation cycle.

Extensive tests were made of the distortion encountered in the recovered weaker-signal modulation under a wide variety of modulation conditions for an $\underline{a}$ of 0.5, at which the feedforward technique delivers its best weaker-signal capture performance. The results indicate that in general considerable distortion of recovered weaker-signal modulation is an inherent feature of the feedforward technique, and that the use of large deviation ratios and receiver audio filters flat over the passband of interest and falling off sharply outside the passband are generally necessary to reduce distortion to tolerable levels.

The best experimental feedforward receiver built was designed for $\pm$ 75 kc frequency deviation on both weaker and stronger signals, and used an audio filter whose response was flat from 300 to 3000 cycles and fell off sharply outside this band. At an $\underline{a}$ of 0.5, the measured distortion on recovered weaker-signal modulation varied between 10 per cent and 30 per cent, depending on the two modulating frequencies involved and the peak deviation of the two signals. Reduced weaker-signal deviation resulted in reduced distortion down to one-half or one-third full deviation. Reduced stronger-signal deviation with full deviation on the weaker signal resulted generally in increased distortion. Distortion was fairly uniformly distributed as a function of weaker-signal modulating frequency over the filter passband. The distortion conditions were such as to allow usuable and completely intelligibile (but not high-quality) speech transmission on the weaker signal at an a near 0.5 with the experimental feedforward receiver used for reception.

A feedforward receiver designed for weaker-signal capture would be at its best in a situation in which it was required to capture a weaker signal with a near 0.5 whose deviation was about half that of the interfering stronger co-channel signal and whose modulation consisted of one or more narrow-band audio signals such as teletype, remote control, or low-rate digital signals, allowing the use of high deviation ratios and narrow audio filters. The receiver would also be useful for communication-quality reception of a speech-modulated weaker signal, but would not do well with high-quality program modulation, such as music.

The major engineering problems in designing and building a feedforward receiver are: design of limiters and bandpass filters whose parameters remain within the tolerances required for small a; design of a high-performance demodulator to use following the feedforward;

and design of an auxiliary circuit which will maintain complete interference cancellation in spite of variations in input signal amplitude, interference ratio, and circuit parameters.

If vacuum tubes are to be used in a feedforward receiver, the transformer-output circuit of Figure 14, Chapter 4, is probably the simplest and least complicated circuit available; it is capable of good performance if the output transformer is designed carefully and the preceding stage has enough output to insure adequate limiter drive and is not adversely affected by limiter loading. The driver-limiter circuit (Figure 15, Chapter 4) seems to be the basic feedforward design capable of best performance, though it uses a minimum of three tubes instead of two. One untried idea of great promise is the use of two amplifier stages in the upper channel with two very fast silicon computer diodes between the amplifiers as a limiter.

CHAPTER 7

SUGGESTIONS FOR FURTHER WORK

Because of the newness of the feedforward technique, there are many unsolved problems connected with the design of practical feed-forward receivers. A number of ideas for future investigations arose out of the present study because of its exploratory and problem-defining nature.

Improved Narrow-Band Limiters

So far, no one has designed or built a narrow-band limiter which has a low threshold, high output, flat limiting characteristic, freedom from precise adjustments and selected components, a high enough input and output impedance to use easily with tuned circuits, and is simple and economical. Ideally, a single stage should suffice. A few two-stage limiters have exhibited fairly good perfomance at the cost of com-plexity.

One possibility is the use of a special gated-beam tube of the 6BN6 type intended solely for limiter application, with its parameters controlled tightly enough in manufacture to insure uniformly flat limiter characteristics and low thresholds without special bias adjustments or tube selection. This obviously involves considerable design effort.

The use of diodes in a narrow-band limiter is worth investigating. Most previous diode limiters for FM receivers were wideband and used diodes which are now obsolete. Recently developed semiconductor devices such as Zener diodes, tunnel diodes, and silicon computer diodes deserve study as possible limiter components. An interesting possibility is the Microwave Associates IN903 silicon diode, which has extremely fast switching time, uniform characteristics, and the inherent 0.5 volt gap before forward conduction found in silicon diodes which makes bias unnecessary. Two diodes connected in parallel with opposite polarities constitute a limiter which saturates at 1 volt peak to peak. The problem with diode limiters is to reconcile their low impedance with the necessity for reasonably high-impedance tuned circuits and the high voltage output necessary to adequately drive the next limiter.

Improved Bandpass Filters

In designing feedforward systems, special attention must be given to the bandpass filters used (see Chapter 2). Double-tuned circuits can be used in many cases if properly designed with adequate thought given to stability, ease of adjustment, and freedom from loading effects. One attractive untried possibility is the use of potted toroidal inductors, silver mica capacitors, and mutual-capacitance coupling, insuring great stability and ease of adjusting coupling coefficients.

Demodulator Improvements

As mentioned in Chapter 4, better limiters would have improved the performance of the demodulator described there. An improvement in demodulator capture performance is reflected in improved feedforward receiver performance. However, demodulator performance improvements become less and less important as the capture ratio is pushed toward 1.0, since the range of a over which distortion occurs becomes so small. Therefore, work on improved demodulators is valuable up to a point, beyond which it is not worth the effort.

Automatic Control Systems For K

As mentioned in Chapter 2, a feedback system which would automatically adjust K for best weaker-signal capture as determined by the quality of the demodulator output would be an extremely valuable addition to a feedforward receiver. Such a system would be somewhat complex, but would enhance performance materially.

One difficulty with the scheme is the problem of building a system which can accurately determine the point of correct adjustment. The most obvious scheme is to transmit a pilot tone on the desired signal, outside the audio bandwidth used. Maximum amplitude of this pilot tone at the demodulator output indicates the optimum value of K, the tone being separated from the message modulation by a narrow filter. The outstanding advantage of this idea is that if the control system is designed to sweep slowly from K = 0 to slightly below K = 1, stopping at the point of maximum pilot tone output, it would adjust K for optimum desired-signal capture regardless of whether the interference was stronger or weaker.

Figure 1 shows a block diagram of a proposed control system embodying the above ideas. The sawtooth generator is a phantastron sweep circuit of the type used in "search" type radar AFC[16]. It generates a negative-going sawtooth waveform until a negative "stopping"

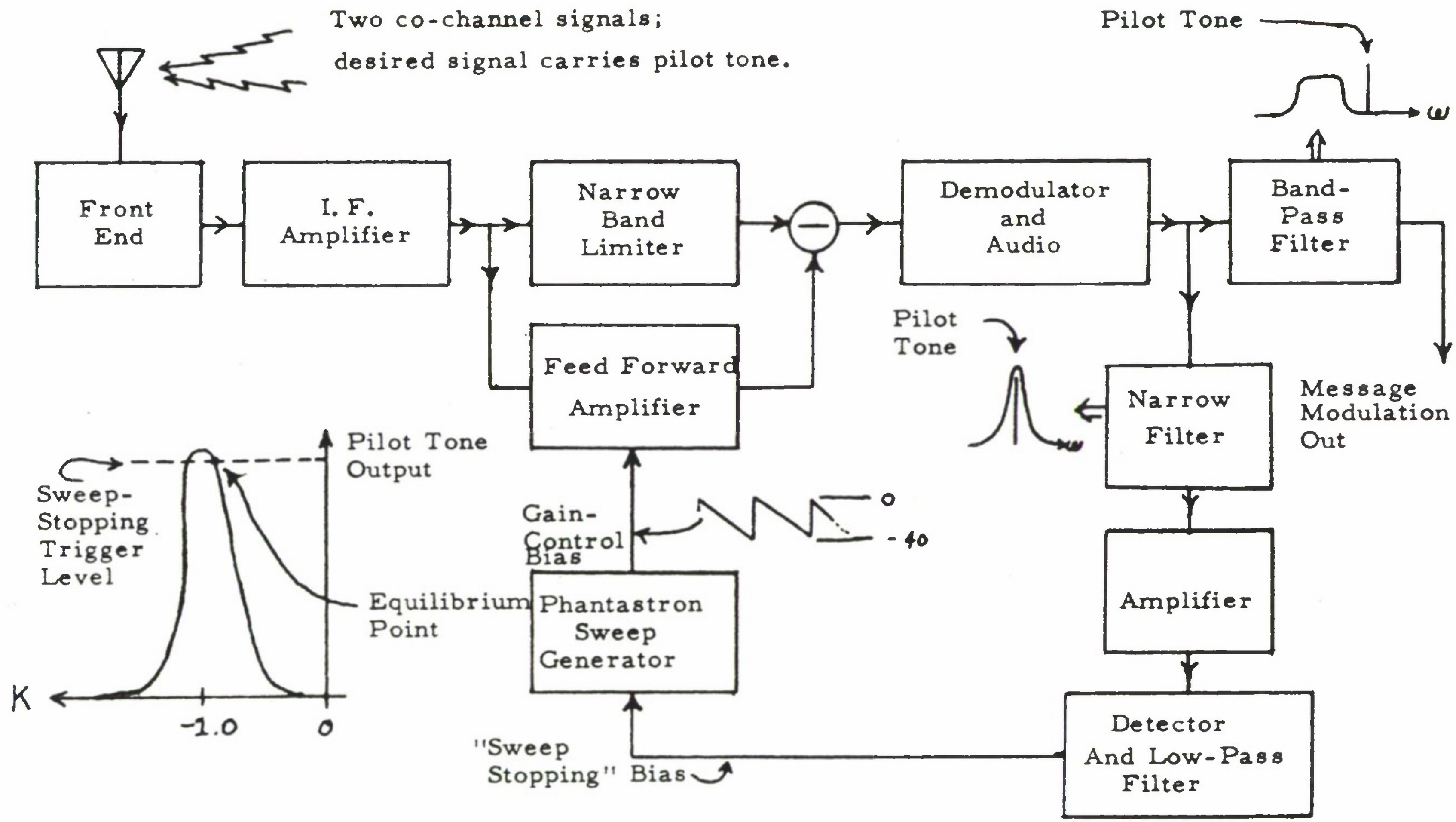


Figure 1

Block Diagram of a Proposed Control System to Automatically Maintain Interference Cancellation bias is applied to its control terminal, at which time the circuit becomes a DC amplifier, its steady output level being directly proportional to the "stopping" bias. The output of the pilot-tone filter is rectified to provide this stopping bias. The sweep generator output is applied as bias to the feedforward amplifier grid, causing the gain of the amplifier to sweep from a maximum down to zero and thereby varying K from below -1 up to zero.

The graph in Figure 1 shows how an equilibrium point would be reached slightly below the optimum value of K. An extraneous influence acting to push K toward K_{max} would result in greater output from the pilot tone filter and increased negative bias on the sweep circuit (now behaving as an inverting DC amplifier), raising its output level and decreasing feedforward amplifier bias to increase its gain and move K upward to compensate for the disturbance. An extraneous drift of K in the other direction would be similarly compensated.

If K suddenly moves past K_{max} faster than the system can compensate or the pilot tone output falls below the triggering level due to worsened interference, the sweep generator will start, moving K away from the equilibrium point. Presumably, the system will lock in on the next sweep cycle at a new value of amplifier gain. The demodulator output level at which the sweep actually stops is subject to so many extraneous influences that it is probably best provided as a front panel control which could be adjusted until the system barely locked in.

The system as it stands has the disadvantage that it will not hold K at its exact optimum value but at some nearby value. This might be gotten around in a more refined system which could determine the point of best adjustment exactly, either by the pilot-tone method or by some other technique.

Reducing Audio Distortion

The results of Chapter 5 show clearly that sinusoidal modulation on the weaker of two co-channel signals can be recovered with practically its full amplitude. However, it will inherently be accompanied by a fairly sizable amount of distortion, no matter how good the R. F. portions of the feedforward receiver. Therefore, methods of reducing the audio distortion would be very valuable.

Since the captured modulation waveform is intact over a part of the cycle and "broken up" over discrete segments of the waveform, the "speech repair" techniques used by Arguimbau, et al.[15] in their transatlantic FM experiments might be of value. Briefly, their technique consisted of replacing the violently disturbed portions of the waveform with linear approximations based on the value of the modulation waveform and its derivative just before onset of the disturbance.

In a system in which a strong FM signal with speech or music modulation occupied a channel all or part of the time, it might be possible to effectively utilize a weaker signal on the same channel to transmit remote control signals, teletype signals, or low-rate digital information with good results, since such signals allow the use of narrow audio filters following the weak-signal capture receiver, minimizing the inevitable audio distortion. By careful choice of audio frequencies, it should be possible to transmit several such narrow-band signals on a single carrier without undue crosstalk. Investigation of this possibility would not be difficult, given a reasonably good feedforward receiver capable of weaker-signal capture.

More Complex Systems Based on the Feedforward Principle

It has been suggested previously that if the simple narrow-band limiter of Figure 5, Chapter 1 were replaced by a more effective device for reducing the interference ratio of two signals at its input, the amplitude differential at the point of subtraction would be larger, increasing the amplitude of the residual weaker-signal component in the output and hopefully increasing the fraction of the modulation cycle over which weak signal capture could be achieved.

One suggested replacement for the single limiter is another entire feedforward circuit arranged to improve the predominance of the stronger signal. The phasing problem involved in such a scheme would be its most unattractive feature. It would also be advisable to determine by theoretical analysis whether or not the potential improvement in the amplitude of the residual weaker-signal component would actually allow weaker-signal capture over a significantly larger fraction of the modulation cycle before going to the trouble of building such a device; if not, it would offer no improvement over the simpler system. The feedforward used to replace the limiter could be the pre-limiter type, since the pre-limiter offers no disadvantage in a stronger-signal feedforward.

Another possible replacement for the single limiter is a cascade of two or more narrow-band limiters. Phasing problems are troublesome in this scheme, also. If two limiters are used with a double-tuned inductively coupled circuit between as a bandpass filter, a 90° phase lead must be introduced into the amplifier channel because of the 90° phase lead introduced by the double-tuned circuit over its pass-band. All sorts of increasingly complex schemes can be worked out which will yield the proper phase relationships. The next most complicated possibility uses three limiters in the upper channel with doublt-tuned inductively-coupled circuits between, resulting in zero net phase shift and allowing the use of a single stage feedforward amplifier. If too many limiters are included in the upper channel, however, envelope delay will become troublesome; the origin and effects of this trouble are described by Gutwein[11].

Theoretical evaluation of the performance to be expected from the cascaded-limiter feedforward awaits a detailed analysis of the spectrum at the output of a cascade of two or more narrow-band limiters with two-signal input for the case in which more than the original two components are included within the filter passbands.

The "Ultimate" Basic Feedforward

From a knowledge of the circuit problems usually encountered and the requirements on the basic components (see Chapter 2), it is possible to outline the salient design features of a practical feedforward receiver whose performance should approach that of an ideal system.

The I. F. amplifier would employ a crystal or mechanical filter in order to approximate as closely as possible the desired rectangular passband shape and be free of alignment adjustments. The filter would be isolated from the feedforward limiter by at least one linear amplifier stage with a broadband, low-impedance output circuit so that the I. F. passband would be unaffected by limiter loading. The limiter would be of the "improved" type specified earlier in this chapter, and would be followed by a second mechanical or crystal filter of nearly rectangular passband shape, well isolated as was the first. The demodulator should have a capture ratio as high as possible; three or four properly designed narrow-band limiters plus a wideband limiter and discriminator of 5 or 6 I. F. bandwidths should do the job. An automatic control system would be included capable of maintaining the optimum value of K for any usuable input signal strength and for all values of a above some small a_{min}, including $a > 1$, when a pilot tone is used. It should be possible to automatically maintain a manually preset value of K independent of input signal variations when no pilot tone is present on either input signal.

Construction of such a receiver, using either tubes or transistors, is well within the state of the art but would require considerable development effort and would be rather costly. Its performance capabilities, however, should be quite useful, as well as interesting.

Feedforward Demodulator

A basic feedforward for stronger-signal capture could be built with three tubes: a pre-limiter, a feedforward limiter, and a feedforward amplifier. The output of the feedforward could be fed to a wideband limiter-discriminator combination or, conceivably, directly to an amplitude-insensitive FM detector such as a ratio detector or gated-beam discriminator. The combination would constitute a demodulator with a reasonably good capture ratio. It would be very interesting to compare the performance of this "feedforward demodulator" with the performance of a conventional chain of narrow-band limiters plus wideband limiter and discriminator which used the same number of tubes. It seems possible that the feedforward might offer better performance than the straightforward chain of limiters using the same number of tubes; if so, its greater complexity would be justified. An experimental investigation to settle this question would not be difficult and its results would be quite valuable.

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13. ABSTRACT

The feedforward signal-cancellation technique is based on subtractively combining the outputs of limiters and linear amplifiers having a common input. Used in an FM receiver, feedforward provides an attractively simple and effective method for suppressing interference to an FM signal from other co-channel or adjacent-channel signals which may be either weaker or stronger than the desired signal. The thesis explores theoretically and experimentally the potential performance and inherent limitations of practical FM receivers using feedforward. Design criteria are discussed for various interference conditions and the relative merits of several practical feedforward circuits are considered.

A laboratory model FM receiver was built and tested with three different feedforward circuits, its performance being measured under a variety of interference conditions. Significant improvement in the stronger-signal capture performance of a mediocre FM demodulator was demonstrated. Sinusoidal modulation was recovered from FM signals between 0.05 and 0.9 times the amplitude of an interfering signal on the same channel, distortion ranging generally between 8 per cent and 30 per cent for various interference conditions. Completely intelligible speech modulation was also recovered from the weaker of two co-channel FM signals. Numerous suggestions for further work are given.

14. KEY WORDS

interference   FM receivers   feedforward   demodulation