Performance Characteristics of FM Detector Systems

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An analysis of operating features of two classes of currently used detection methods for FM receivers—Advantages of each

THIS article describes the general performance characteristics of some of the frequency modulation detector systems of current interest. A detector system using a diode as a dynamic limiter, and having a variable threshold level, is described. This is followed by a review of the characteristics of the better known frequency modulation detector systems, such as those using grid-bias limiters, locked oscillators and ratio detectors.

• This paper is intended primarily to discuss the performance characteristics of various FM detector systems which may have a direct effect upon the design and manufacture of FM receivers. Such performance characteristics include:

1—AM rejection properties, which relate to noise rejection and reduction of distortion due to amplitude modulation from IF selectivity and multi-path transmission.

2—Variation of audio output with carrier level.

3—The tuning characteristics of a receiver using the detector under consideration.

In illustrating these properties for the various detector systems, certain representative over-all performance characteristics are shown. It should be appreciated that while some of their overall characteristics are similar, the several systems differ appreciably in their mode of operation, and consequently differ in structure and in other performance respects.

When sensitivity is considered in terms of audio output voltage vs. input carrier voltage for a given percentage of modulation and similar AM rejection capabilities, all of the various detector systems discussed herein have sensitivities of a similar order of magnitude. Also, by appropriate design, it is possible to obtain very satisfactory detection linearity from the various detector systems.

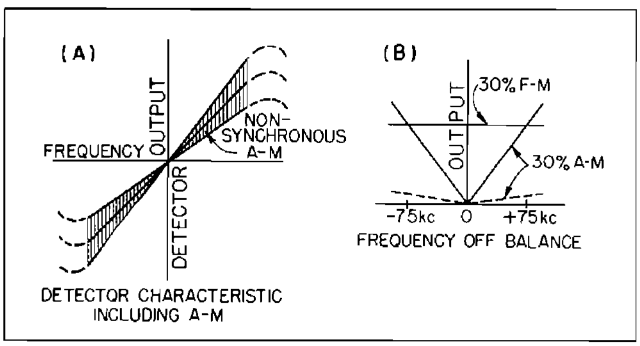
Most FM detector systems include the equivalent of the balancing action of a balanced discriminator. With a balanced discriminator the AM output is zero at center frequency and is proportional to the frequency deviation from balance, as illustrated by the detector characteristic of Fig. 1A, and shown by the solid curves of Fig. 1B. When an FM detector system exhibits some AM rejection properties, the AM output may be expected to vary similar to the dotted curve in Fig. 1B.

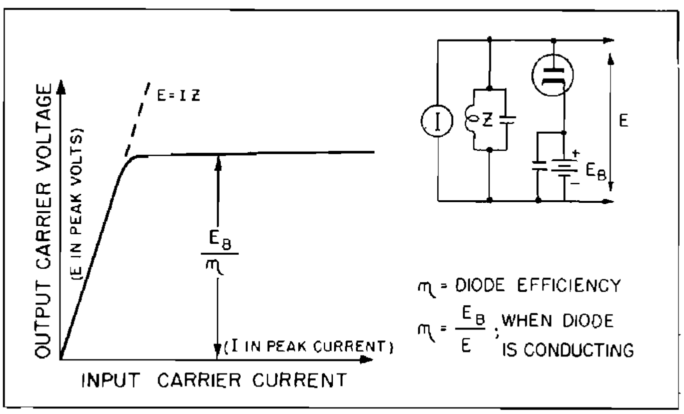
In this paper the term "AM reduction factor" refers to the ratio of the AM output of a detector system exhibiting AM rejection properties to the AM output of an ideal balanced discriminator. The AM reduction factor is generally substantially independent of frequency deviation, but in certain special cases when this is not true, it may be expressed as having different values for large and small amounts of FM. Also when perfect balance is not obtained, this is generally due to a different set of detector deficiencies which are best analyzed separately.

It is convenient to know two characteristics of the AM rejection action of a detector system:

1—The "AM Reduction Factor," which is the ratio of the percentage AM of the output to the per-

Fig. 1—Characteristics of a balanced discriminator
Fig. 2—Diode limiter as a fixed threshold limiter





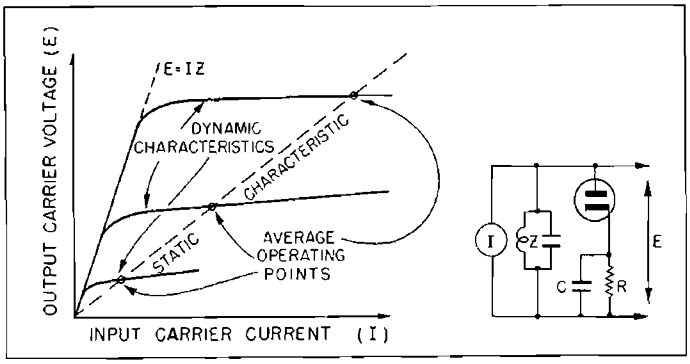


Fig. 3—Limiter characteristics for a dynamic limiter

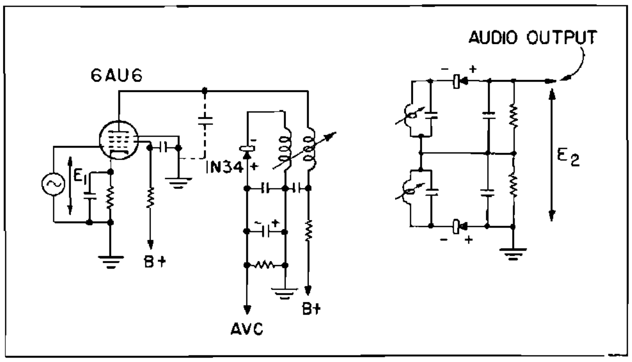


Fig. 4—FM detector using dynamic limiter with germanium diodes

centage AM of the input signal exclusive of the balanced discriminator action, for a small percentage of input AM. This relates to the rejection of such small AM as results from fluctuation noise at normal signal levels.

2—The "Downward AM Capability," which is the percentage of downward AM which produces a certain significant change in output signal amplitude, such as that due to the instantaneous signal level falling below the threshold. This relates in particular to the detector performance under conditions of large AM, such as may be due to multi-path transmission or to the IF selectivity. When a smooth or indistinct threshold exists, the downward AM capabilities are expressed, in this paper, in terms of the downward AM of the input signal which produces 25% AM of the output signal.

The Dynamic Limiter

An interesting type of FM detector system can be produced by using a diode for a limiter and following this by a balanced discriminator. An effective voltage limiter of the fixed threshold type can be produced by placing a biased high-conductance diode in shunt with a high impedance resonant circuit, as shown in Fig. 2.

As the applied signal current is increased, the output increases until the peak output voltage equals the diode bias voltage. As the input is increased beyond this threshold level the diode conducts, producing an increasing damping effect which regulates for approximately constant output. If the circuit Q is high, the damping is in effect integrated throughout the rf cycle so that a single diode, conducting on one peak, can be used. By using a high-conductance diode and a high-impedance tuned circuit the regulation is predominately in the tuned circuit impedance with only a small voltage drop resulting across the diode. This results in a fairly flat voltage limiting characteristic.

If the bias battery is replaced by a long time constant resistor-condenser network, as shown in Fig. 3, a variable threshold device results. The effective bias voltage is now proportional to the average carrier level, its exact value being determined by the resistor value relative to the tuned circuit impedance. However, for dynamic or sudden changes, the bias voltage is held constant by the large condenser, thus producing effective limiting for dynamic changes in the applied carrier signal, as illustrated in Fig. 3. It will be seen from this that the resulting output from the diode dynamic limiter is a carrier whose amplitude is proportional to the average value of the applied carrier current, but as a result of dynamic limiting is relatively free of audio frequency amplitude modulation of the applied carrier.

By following the dynamic limiter by a balanced discriminator, an FM detector system is produced which has a variable threshold level and an audio output which is proportional to the applied carrier level. A practical detector system can be made using a germanium crystal diode for the voltage limiter, this diode having a rather high conductance. Fig. 4 shows such a detector system which uses side-tuned circuits and crystal diodes for the balanced discriminator. It should be noted, however, that the conductance of the discriminator diodes is relatively unimportant as they can operate with rather high load resistors, and only the limiter diode need have high conductance.

Typical performance characteristics for this dynamic limiter detector circuit are shown in Fig. 5. The audio output and AVC voltages are approximately proportional to the input signal level. The AM rejection resulting from dynamic limiting varies smoothly with signal level, becoming better with increasing signal level because of increased diode efficiency. The resulting AM reduction factor, which for small percentages of AM is related to the slope or first derivative of the input-output characteristic of the limiter at the particular average carrier level, is shown in Fig. 5C. It should be noted that the AM reduction factor usually will not become negative in this device at any signal level.

Threshold Level

The downward AM capabilities, shown in Fig. 5D, tend to remain constant with changes in average signal level because of the variable threshold level. However, in this device, as in the ratio detector, the downward AM capabilities reduce at very low signal levels due to lack of AM rejection resulting from low diode efficiency. It is interesting to note that back conduction in a crystal diode used as a limiter merely supplements its limiting characteristics.

It is apparent from the above discussion that the dynamic limiter detector system has a variable threshold level, with a variable output and a downward AM capability which is relatively fixed. The effects of these characteristics upon the tuning characteristics of a complete receiver are interesting.

As the carrier is detuned, the audio output reduces due to a reduction in carrier level, at the detector, resulting from IF selectivity. This

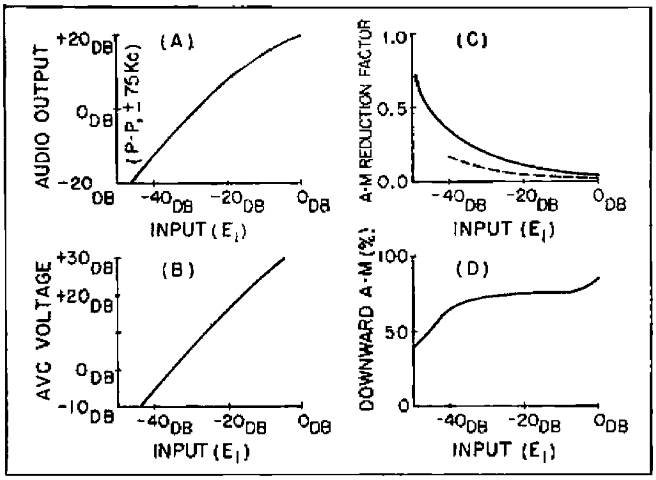


Fig. 5—Dynamic limiter characteristics

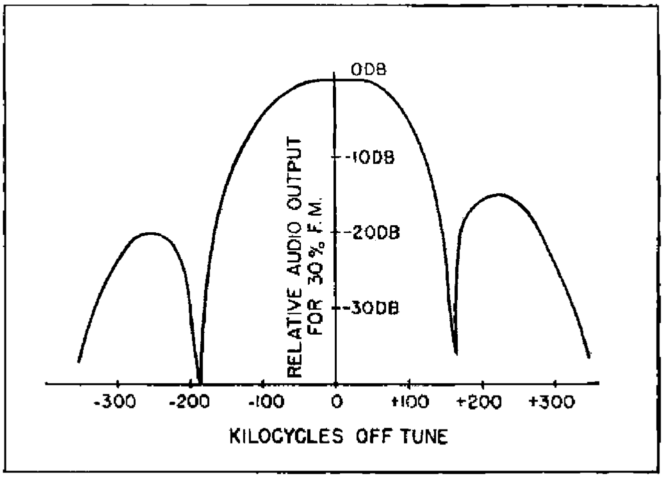


Fig. 6—Typical tuning characteristics for an FM receiver using a dynamic limiter

fact, in conjunction with the fact that the AM rejection reduces only gradually as the signal level is reduced, can result in a significant reduction in the side response amplitude and relatively little interstation noise.

As an illustration, a typical tuning characteristic for a receiver using a dynamic limiter detector system is shown in Fig. 6. However, the amount of reduction of the side-responses, and of the inter-station noise, is determined by the AVC characteristics of the particular receiver. A receiver designed with a rounded top IF response and with a detector having wide peak separation permits the tuning characteristic to have a peak in audio output when the signal is on tune, and reduces the side responses.

Dual Diode Limiter

While a single limiter diode can produce significant limiting, the use of a dual diode as limiter can give improved results. In particular when the circuit Q is low, harmonic voltage may develop across the tuned circuit which will affect the limiting action. By using a dual diode limiter, which conducts on both positive and negative peaks, the even harmonic currents are substantially reduced, giving improved dynamic limiting action. An indication of the improved AM rejection which can result is shown by the dotted curve in Fig. 5C.

An interesting detector system can be produced which has cascade means for AM rejection, and has a variable threshold level, by following a dynamic limiter with a ratio detector. Since the resulting system has two means of giving AM rejection, the requirements upon each means are reduced.

This system uses a grid-bias limiter, for limiting amplitude modulation, with a subsequent balanced discriminator circuit for FM detection. The limiter circuit, as illustrated in Fig. 7A, operates by developing a self-rectified grid-bias which narrows the angle of plate current conduction with increasing signal amplitude. In a correctly designed circuit the result is a fundamental frequency output component which, above a certain critical signal level, is approximately independent of input signal amplitude, as shown in Fig. 7B.

When only grid-bias limiting is used, the output is approximately constant over a range of about 20 db of input signal level, but the output tends to again rise for higher input signal levels, as shown by the dotted curve of Fig. 7B. This effect can be reduced by using a low plate voltage to effect plate limiting, or by using a second cascade limiter. When using this double limiting action an input-output characteristic approximately as shown by the solid curve of Fig. 7B can be obtained.

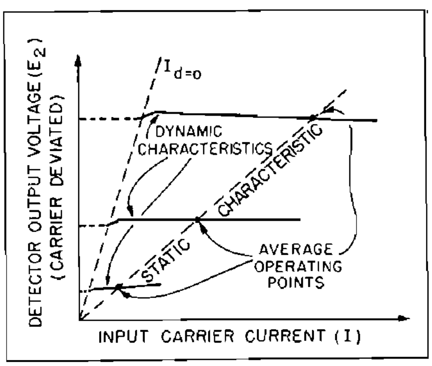


Fig. 10—Input-output characteristics for the ratio detector

The grid-bias limiter is usually designed to have a short time constant in its grid-bias circuit and to have plate and screen supply voltages of fairly good regulation. This produces a device whose input-output characteristic for rapid or dynamic signal level changes (at an audio frequency rate) is similar to that for slow or static changes in average signal level. Thus the knee in the input-output curve occurs at a unique input signal which is relatively unaffected by the applied average signal level, producing a device with a fixed threshold level.

Grid-Bias Limiter

Fig. 7C is the AM reduction factor vs. signal level for the grid-bias limiter, produced by limiting action. This shows that substantially no AM rejection exists below the threshold and that the AM rejection suddenly takes hold at the threshold level because of limiting. It should be noted that a slight over-compensation is common in the limiting region so that a small percentage of reverse polarity AM is frequently produced, as shown by the negative value.

The downward AM capability for the grid-bias limiter is shown in Fig. 7D and is seen to approach 100% modulation as a limit as the signal level is increased. From the above, the grid-bias limiter is seen to be a fixed threshold level device having a fixed output, a downward AM capability which increases with increasing signal level, and an AM

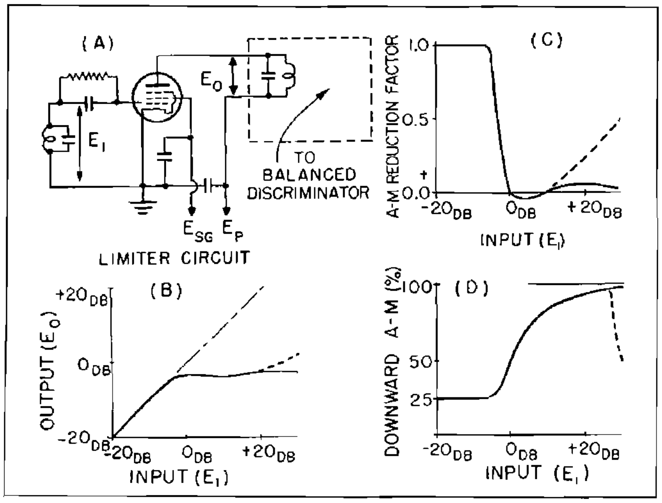


Fig. 7—Grid-bias limiter characteristics

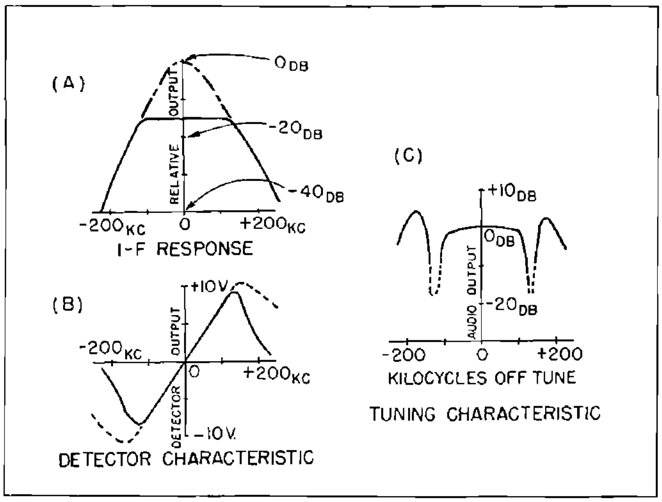


Fig. 8—Typical characteristics of an FM receiver using a grid-bias limiter

rejection by limiting which rapidly becomes effective when the input signal exceeds the threshold level.

The tuning characteristic of a receiver using a grid-bias limiter will next be considered. An IF response curve for a typical receiver is shown in Fig. 8A, the dot-dash curve being the response curve exclusive of limiting and the solid curve the effective response curve with limiting. A typical detector discriminator characteristic as measured with constant input to the limiter grid is shown in Fig. 8B by the dotted curve. When this detector characteristic is taken through the entire receiver, a curve such as the solid curve of Fig. 8B may result.

Audio Output

Here it is seen that as the signal is detuned, the IF selectivity causes the signal level at the limiter to fall below the fixed threshold level and then the IF selectivity curve skirts are effective in increasing the side-slopes of the overall detector characteristic. The audio output due to FM is proportional to the slope of the detector characteristic about the mean frequency of the applied signal. Thus, as the receiver is tuned through an applied signal, the audio output may be expected to vary as in Fig. 8C.

It is not uncommon for the resulting side-responses to be greater in amplitude than the desired response. These side-responses can be reduced in amplitude by reducing the IF selectivity; or, since they are due to the signal level passing below the threshold, they can be masked by noise by including enough gain in the receiver to make the threshold occur at the noise level.

An oscillator which is synchronized by an applied FM signal can be made to reproduce the FM of the applied signal and to be substantially non-responsive to AM. The signal from the locked oscillator can be fed to a conventional discriminator, or the discriminator action can be effectively included within the locked oscillator circuit, so that the combination forms an FM detector system which is non-responsive to AM.

The locked oscillators normally require at least a certain critical applied signal level to effect synchronization and below this level their output signal is relatively unaffected by the applied signal. Thus the input-output characteristic may have a discontinuity at the threshold level giving effectively zero output below this threshold level, at least as far as modulation components are concerned.

The locked oscillator FM detector systems thus have a fixed threshold level with fixed output, and a downward AM capability which increases with increasing signal level. It will be apparent from this that the locked oscillator detector systems have overall resultant characteristics similar to the typical characteristics shown for the grid-bias limiter except that an effective discontinuity may exist at the threshold. This discontinuity may produce a tuning characteristic having high distortion regions instead of side responses.

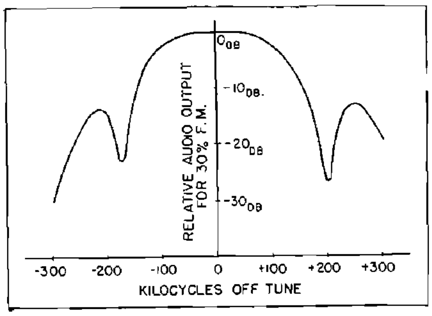


Fig. 12—Typical tuning characteristics for an FM receiver using a ratio detector

The Ratio Detector

The Ratio Detector is a relatively new, but already widely used FM detector system. A conventional form of this circuit is shown in Fig. 9.

This detector has the property that its dynamic and static characteristics are different. The effective input-output characteristics of this device may be measured by applying a statically deviated carrier and measuring the output voltage E_2 vs. the applied carriel level E_1. For slow or static changes in carrier level the output E_2 will vary approximately linearly with input E_1, as shown by the dotted curve of Fig. 10.

This type of detector has the desirable characteristic, however, that it is not responsive to dynamic or sudden changes in carrier level, such as audio frequency amplitude modulation, so that its output will be almost independent of the instantaneous amplitude of the input, as shown by the solid curves in Fig. 10, with the magnitude of the output determined by the average amplitude of the applied carrier.

This difference between dynamic and static characteristics results from the long time constant load circuit, across which the voltage E_B

is developed, this voltage E_B being proportional to the average carrier level and independent of audio frequency AM. The overall result is an output voltage which is proportional to the instantaneous carrier frequency and to the average carrier level but is relatively free of audio frequency AM of the applied carrier. The exact reasons why this detector circuit is non-responsive to AM is considered as being outside the scope of this paper.*

The range of the dynamic input-output characteristic has a limitation, for upon downward amplitude modulation the instantaneous carrier voltage applied to the diodes may be exceeded by the back biasing effect of voltage E_B, thus cutting off the diodes. While the resulting dynamic input-output characteristic may give an output voltage when the diodes are cut off, as shown dotted in Fig. 10, this output, however, is a static charge remaining on various condensers, and is no longer capable of being controlled by instantaneous frequency of the applied carrier.

Dynamic Threshold

Thus, there is in effect a sharp dynamic threshold occuring when the diode currents become zero. It should be noted, however, that as the average carrier level is varied, the bias voltage E_B varies and the threshold level for diode current cut-off also varies. The resulting variation in dynamic threshold in response to average carrier level variations tends to keep the downward AM capabilities of the detector system such that they vary only slightly with applied signal level.

Typical operating characteristics of a ratio detector are shown in Fig. 11. It will be noted that the audio output and AVC voltage vary almost directly with the applied signal level. As the average signal level is varied the slope of the dynamic input-output curve changes slowly. The resulting variation of AM reduction factor with average signal level is a smooth curve as illustrated in Fig. 11C which does not have a distinct threshold as far as *average* signal level variations are concerned. It is not uncommon for the slope of the dynamic input-output characteristic to reverse sign at high signal levels giving a small opposite polarity AM output. As indicated previously, the downward AM capabilities vary only slightly with average carrier level as shown in Fig. 11D.

It is apparent from the above discussion that the ratio detector is non-responsive to AM, has a variable threshold level, with a variable output and a downward AM capability which is relatively fixed, and it thus has quite different overall characteristics than the grid-bias limiter detector system. The effects of these differences in performance upon the tuning characteristics of a complete receiver are similar to those with the dynamic limiter detector system, and can result in a significant reduction in the side response amplitude and relatively little inter-station noise. A typical tuning characteristic for a receiver is shown in Fig. **12**.

Based upon their overall resulting characteristics, the currently used FM detectors can be divided into two general classes. The first class having similar overall resultant characteristics includes the grid-bias limiter detector system and locked oscillator arrangements, particularly in that they have a fixed threshold level, a variable output, a down-AM capability which increases with increasing signal level, and an AM rejection which rapidly becomes effective when the input signal exceeds the threshold level.

AM Rejection

The second class, in regard to overall resultant characteristics, includes the ratio detector and the dynamic limiter detector system, in that they have a variable threshold level, a variabel output, a downward AM capability which is relatively fixed, and an AM rejection which varies gradually with variations of average signal level.

In general the input signal level required to produce significant AM rejection in one of the detector systems having a variable threshold level is smaller than that required for one of the systems having a fixed threshold level. However, the application and desired operating characteristics of a particular receiver will affect the class of FM detector which should be used. Besides the cost problem, such questions as the expected degree of multi-path interference, the amount of fading and the desired tuning characteristics should be considered for each application.

*For further details on the ratio detector, see Tele-Tech July, 1947 page 46 to 49.

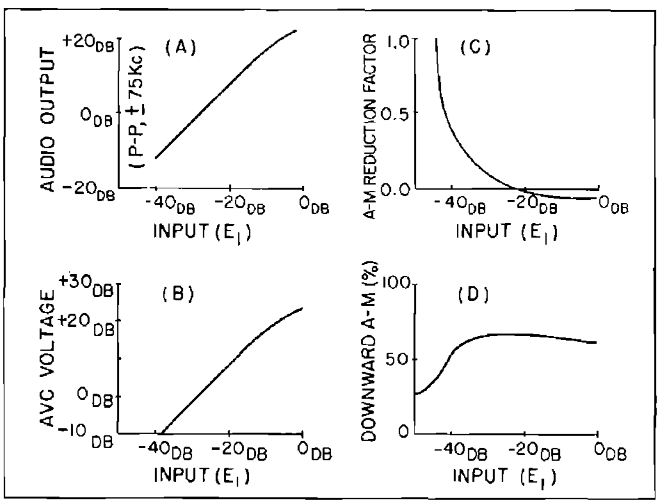


Fig. 11—Ratio detector characteristics

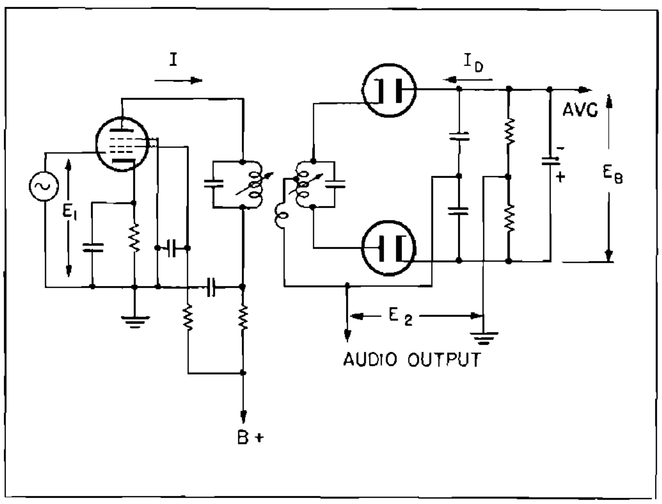


Fig. 9—Circuit diagram of ratio detector