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by

W. G. Tuller and T. P. Cheatham, Jr.

Abstract

If the pentode amplifier normally used to drive a Foster-Seeley discriminator is replaced by a cathode follower, the resultant discriminator circuit takes on new characteristics. Among these are easily adjustable band-width, output-frequency characteristics complementary to the frequency-voltage characteristics of frequency modulated stabilized microwave oscillators, and freedom from critical adjustments. Disadvantages are the possible necessity for an additional tube, and increased distortion. Experimental results check the theoretical derivations made on this device. Curves showing harmonic distortion as a function of deviation are given.

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I Introduction

In the course of research now being done on communication systems, the need arose for a discriminator to be used in frequency modulation receivers of variable band-width. Almost simultaneously the mathematical analysis of a typical discriminator circuit showed a possibility of constructing a discriminator whose band-width would be readily adjustable by means of a tap switch, but whose output vs. frequency characteristics would have a shape independent (in normalized co-ordinates) of discriminator band-width. This possibility was successfully investigated experimentally with the results given in the following report. It is believed that the discriminator may be useful for somewhat wider application than was originally thought, since the circuit has proved considerably more tolerant to misadjustment than conventional types. The good features of the discriminator to be described are:

1. Band-width adjustable over more than four to one range by means of single tap switch.
2. Normalized output voltage vs. frequency characteristic is independent of band-width.
3. Normalized output voltage vs. frequency characteristic may be made the complement of the frequency vs. modulating voltage characteristic of a frequency modulated stabilized microwave oscillator, thereby making possible very good overall system linearity.
4. Circuit is not so critical to slight mistuning as most other discriminators (particularly as regards mistuning of primary).

The discriminator to be described has, however, three compensating undesirable features. These are:

1. One additional high-gm tube may be required as compared to other discriminators.
2. Sensitivity (output volts per megacycle of frequency deviation) is an inverse squared function of band-width while peak output voltage is an inverse function of band-width.
3. Larger band-widths are required for a given amount of distortion than in the case of the Foster-Seeley discriminator.

II Electrical Circuit

The circuit of a typical cathode driven discriminator (as we term this device) is given in Figure I. As can be seen from this schematic diagram, the cathode-driven discriminator operates in the same fashion as the Foster-Seeley[1] discriminator except for one important fact; the stage preceding the rectifier acts as a "constant voltage" source (cathode follower) instead of a "constant current" source (pentode amplifier). This in general, means that the tube driving the discriminator may not give good limiting action, and that hence the circuit shown in Figure I may have to be preceded by a conventional limiter. The coils forming the transformer in the cathode driven discriminator may be coupled as tightly as possible, since the output of the discriminator is proportional to the coefficient of coupling between them and the band-width is independent of this coefficient. Values of circuit parameters given in Figure I are for operation at a mid-frequency of 60 megacycles per second, and all data given were taken about this mid-frequency. The remainder of the circuit is believed self-explanatory.

III Theory of Operation

An analysis of the operation of a cathode-driven discriminator is partially given as an incidental part of a published analysis[2] of the Foster-Seeley discriminator and will not be repeated here. The results of this analysis, however, are of interest. If the detectors are linear, the output voltage as a function of circuit parameters is

$$E_0 = \eta E_1 \left\{ \sqrt{\left[1 + \frac{\alpha Q_2 F}{2(1+Q_2^2F^2)}\right]^2 + \left[\frac{\alpha}{2(1+Q_2^2F^2)}\right]^2} - \sqrt{\left[1 - \frac{\alpha Q_2 F}{2(1+Q_2^2F^2}\right]^2 + \left[\frac{\alpha}{2(1+Q_2^2F^2}\right]^2} \right\} \qquad (1)$$

where E_0 = d.c. output voltage

η = rectification efficiency of rectifiers

E_1 = peak r.f. voltage across transformer primary

$\alpha = Q_2 K \sqrt{L_2/L_1}$

Q_2 = loaded Q of transformer secondary

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1 Foster, D. E. and Seeley, S. W. - Automatic Tuning, Simplified Circuits, and Design Practice. Proc. IRE, 25, March, 1937, p. 289

2 Sturley, K. R. - The Phase Discriminator. Wireless Engr. 21, No. 245, pp. 72-78, Feb. 1944.

CATHODE DRIVEN DISCRIMINATOR
(f_m = 60 Mc/s)

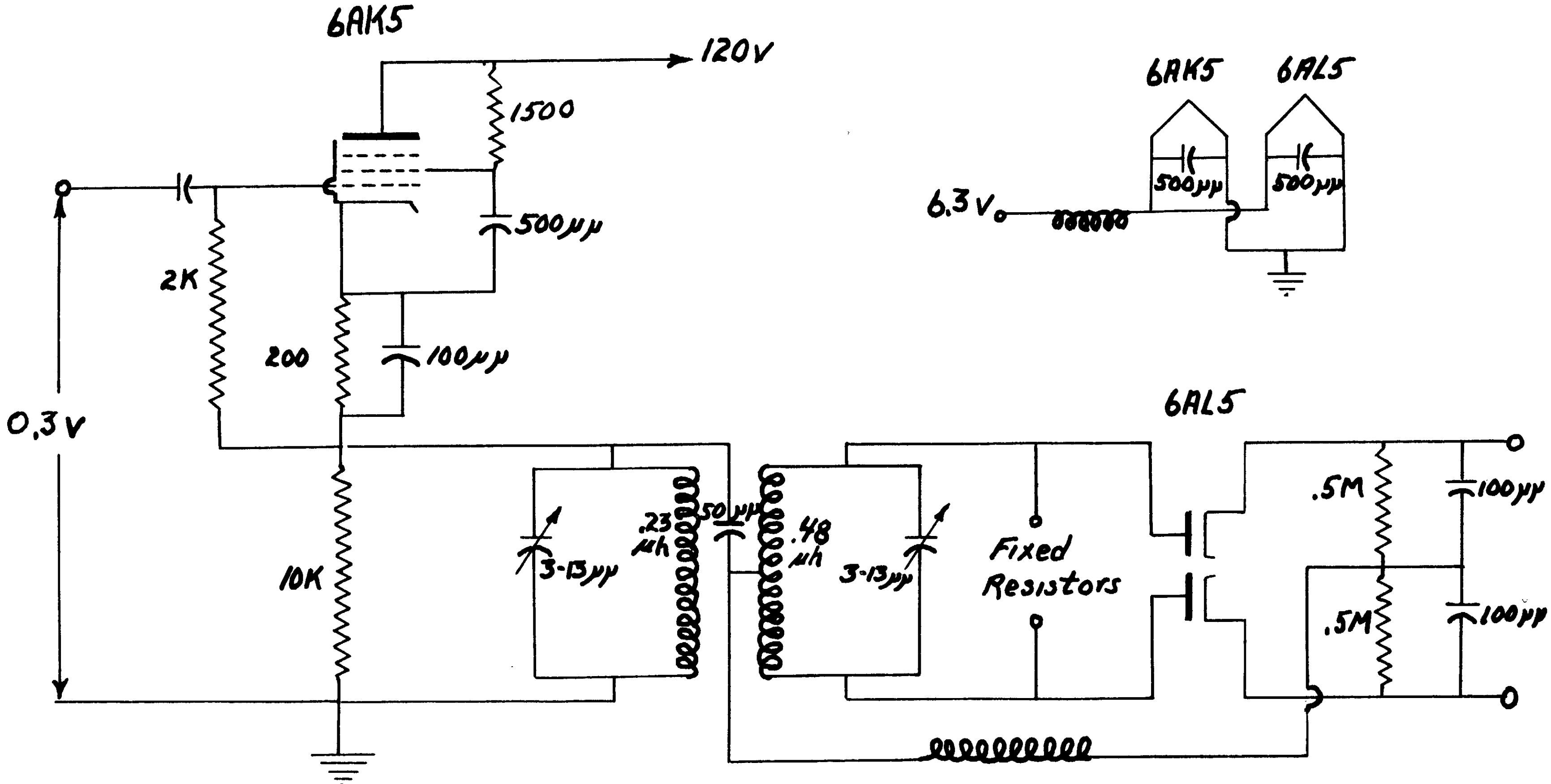

FIG. I

K = coefficient of coupling

L_2 = inductance of transformer primary

L_1 = inductance of transformer secondary

$F = \frac{2B}{f_m}$

B = deviation

f_m = mid-frequency

Each radical in equation (1) represents the output of one of the two half-wave rectifiers. The expression may be simplified to:

$$\frac{E_0}{\eta E_1} = \sqrt{1+\alpha\frac{\frac{\alpha}{4}+Q_2F}{1+Q_2{}^2F^2}} - \sqrt{1+\alpha\frac{\frac{\alpha}{4}-Q_2F}{1+Q_2{}^2F^2}} \qquad (2)$$

Now if the detectors are square law instead of linear, the effect on (2) is simply to remove each radical, leaving

$$\frac{E_0}{\eta E_1} = \frac{2\alpha Q_2F}{1+Q_2{}^2F^2} \qquad (3)$$

From this expression it is apparant that a plot of $\frac{E_0}{\eta E_1\alpha}$ as a function of Q_2F, or, since $F = 2B/f_m$, a plot of $\frac{E_0}{\eta E_1\alpha}$ as a function of Q_2B, should be independent of Q_2. The effect of a change in Q_2 will be to produce a proportional change in the peak amplitude reached by E_0, since α depends directly on Q_2, and to change $\Delta\nu_p$, the peak-to-peak band-width of the discriminator inversely with Q_2, since the output will be a maximum for a given value of Q_2B independent of Q_2. It should be noted that the curve given by (3) is identical with the voltage-frequency characteristic of microwave discriminators, and hence complementary to the frequency-voltage characteristic of a frequency modulated microwave oscillator stabilized by such a discriminator.[3]

As can be seen from a comparison of (2) and (3), the use of linear detectors instead of square law makes the shape of the output-frequency characteristic somewhat dependent on the value of α, and hence on the Q of the tuned

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3 Tuller, W. G. - Distortion in F. M. Discriminators, Technical Report No. 1, March 8, 1946, NDRC Division 14, Research Laboratory of Electronics, Massachusetts Institute of Technology.

circuit. For small deviations (normalized with respect to peak deviation), or for coefficients of coupling less than critical, the difference between linear and square law rectifiers is negligible.

IV Experimental Results

The results obtained from the circuit of Figure I are shown graphically in Figures II and III. Figure II is a normalized plot of the output voltage-frequency characteristic of the cathode-driven discriminator for various loadings, in comparison with two curves taken at different loadings on a Foster-Seeley discriminator. As is apparent from these curves, and as is well known, the shape of the characteristic of the Foster-Seeley discriminator is a critical function of loading and coupling, optimum damping being somewhere, between the no-load (circuit losses correspond to 3200 ohm shunt resistor) and loaded (equivalent shunt resistance of 760 ohms.) conditions, in the case studied. The normalized curves for the cathode driven discriminator, however, are independent of loading within experimental error, as is shown in Figure II.

Figure III is a plot of the product of the band-width and load resistance as a function of the band-width. (Table I is included for supplementary data not included on Figure III). If the circuit Q were infinite, so that all losses were supplied by the loading resistor, this curve should be a straight line parallel to the abscissa, since in this case $Q_2 = \omega LR$ and therefore $R\Delta\nu_p$, where $\Delta\nu_p$ is peak-to-peak band-width, should be independent of R or $\Delta\nu_p$. In practice, however, circuit losses provide a lower limit to the obtainable band-width. In the case investigated this came at 1.7 megacycles, equivalent to a shunting resistance of 3200 ohms. This resistance was assumed to be included in parallel with the various load resistors, the resistance of the parallel combination was computed for each case, and a new curve plotted using the calculated resistance as the load. As is seen in Figure III, the resulting curve, is, within experimental error, a straight line parallel to the abscissa, as indicated by the theory. The load resistors used were measured at D.C. rather than 60 mc/s., so that the A.C. resistance of the highest resistance units might be expected to be relatively lower than the A.C. resistance of the lower units, because of the Boella effect. This might explain the dropping off of the experimental points for small band-widths.

Adjustment of the cathode-driven discriminator to give symmetrical curves was considerably easier than adjustment of the Foster-Seeley discriminator in all cases. This was especially true with respect to primary tuning in obtaining a symmetrical curve about fm.

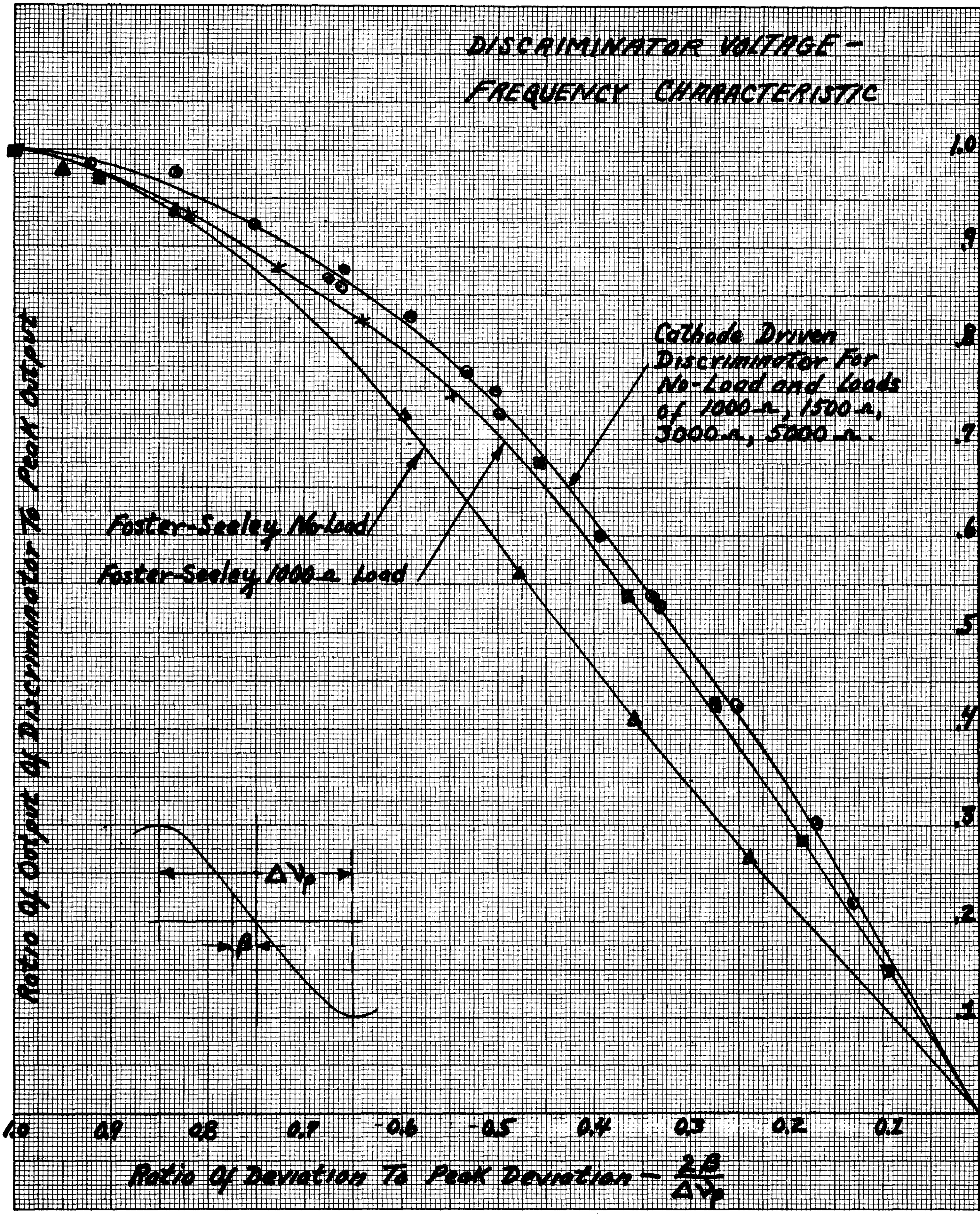
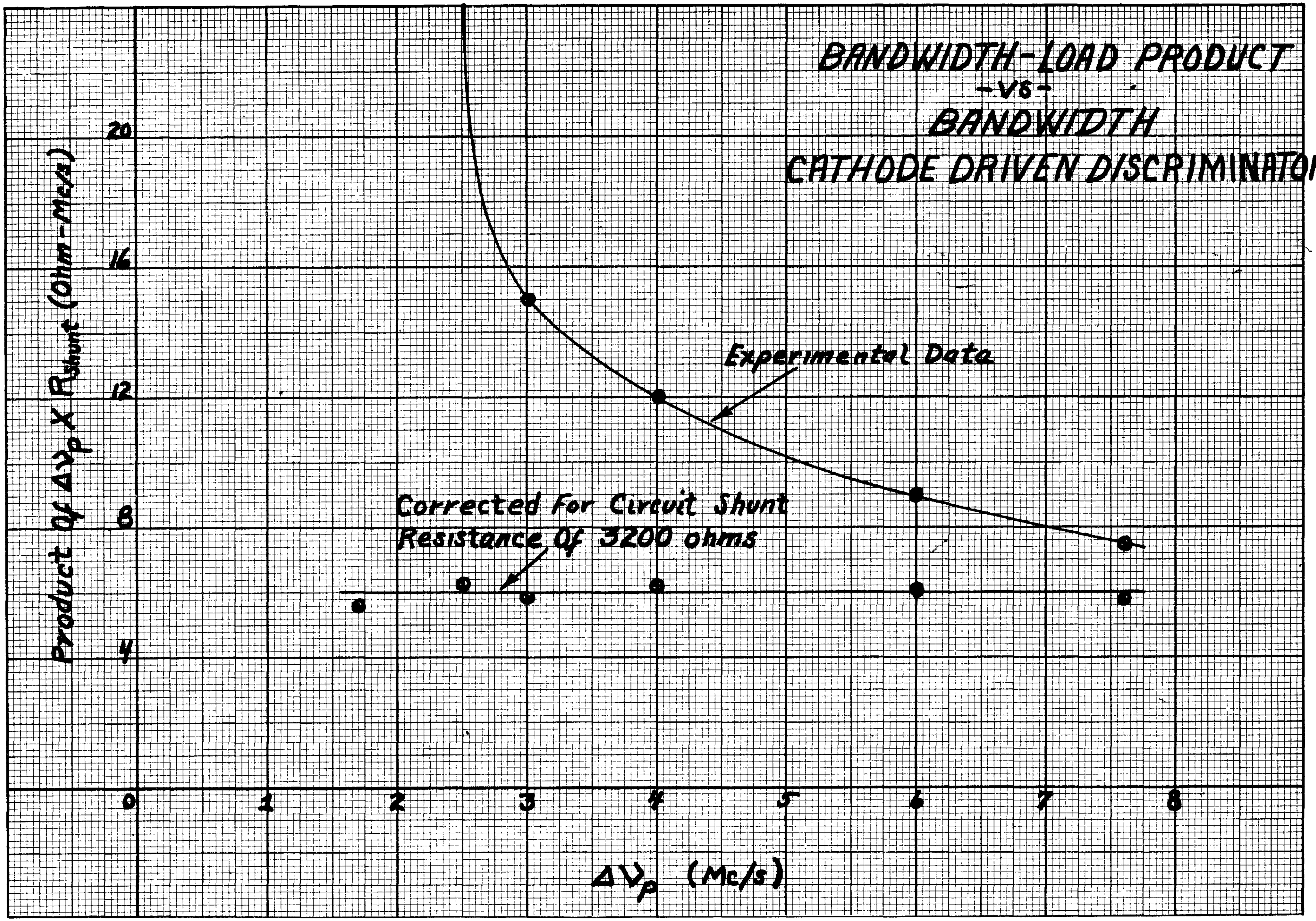

DISCRIMINATOR VOLTAGE -
FREQUENCY CHARACTERISTIC
Cathode Driven
Discriminator For
No-Load and Loads
of 1000-Ω, 1500-Ω,
3000-Ω, 5000-Ω.
Foster-Seeley No-load
Foster-Seeley 1000-Ω Load
Ratio Of Output Of Discriminator To Peak Output
Ratio Of Deviation To Peak Deviation — 2β/Δνp
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
Δνp
β

FIG. II



BANDWIDTH-LOAD PRODUCT
-VS-
BANDWIDTH
CATHODE DRIVEN DISCRIMINATOR
Experimental Data
Corrected For Circuit Shunt
Resistance Of 3200 ohms
Product Of $\Delta\nu_p$ X R_{shunt} (Ohm-Mc/s)
20
16
12
8
4
0
1
2
3
4
5
6
7
8
$\Delta\nu_p$ (Mc/s)

FIG. III

V Distortion

Inasmuch as the cathode-driven discriminator is easy to adjust and not critical as to coupling coefficient, one might wish to use it in the detection of frequency modulated signals from some linearly modulated source such as a broadcast station. In this application one is interested in the nonlinearity of the circuit, which will be somewhat greater than that of the Foster-Seeley as one may guess from examination of the output-frequency curves of the two. Figure IV shows the amplitude of the various important harmonic components in the output of the cathode-driven discriminator as a function of the ratio of deviation of incoming frequency to peak-to-peak band-width of the discriminator. These curves are an extension of the ones given previously in an analysis[4] of microwave discriminators, the extension having been carried out by twelve point schedule analysis. As is shown by these curves, the peak-to-peak discriminator band-width must be five times the peak-to-peak deviation for 1% third harmonic distortion or 2.5 times the peak-to-peak deviation for 5% third harmonic distortion. These figures compare with the 1.7 ratio ordinarily used in commercial frequency modulation receivers. The curves given apply for square law detectors, however, and if linear detectors are used, the ratio of 2.5 may be dropped to 2.1 for critical coupling. Distortion is always less with linear than with square law rectifiers in this discriminator, but is somewhat dependent on coupling at high deviations.

TABLE I

Physical Load Resistor	Actual Shunt Resistance Corrected for ckt. $R_s = 3200\Omega$	$\Delta\nu_p$ (Mc/s)
∞	3.2k	1.7
87k	3.09k	2.0
12k	2.53k	2.5
5k	1.95k	3.0
3k	1.55k	4.0
1.5k	1.02k	6.0
1.0k	.76k	7.6

4 Tuller, W. G. - loc. cit.

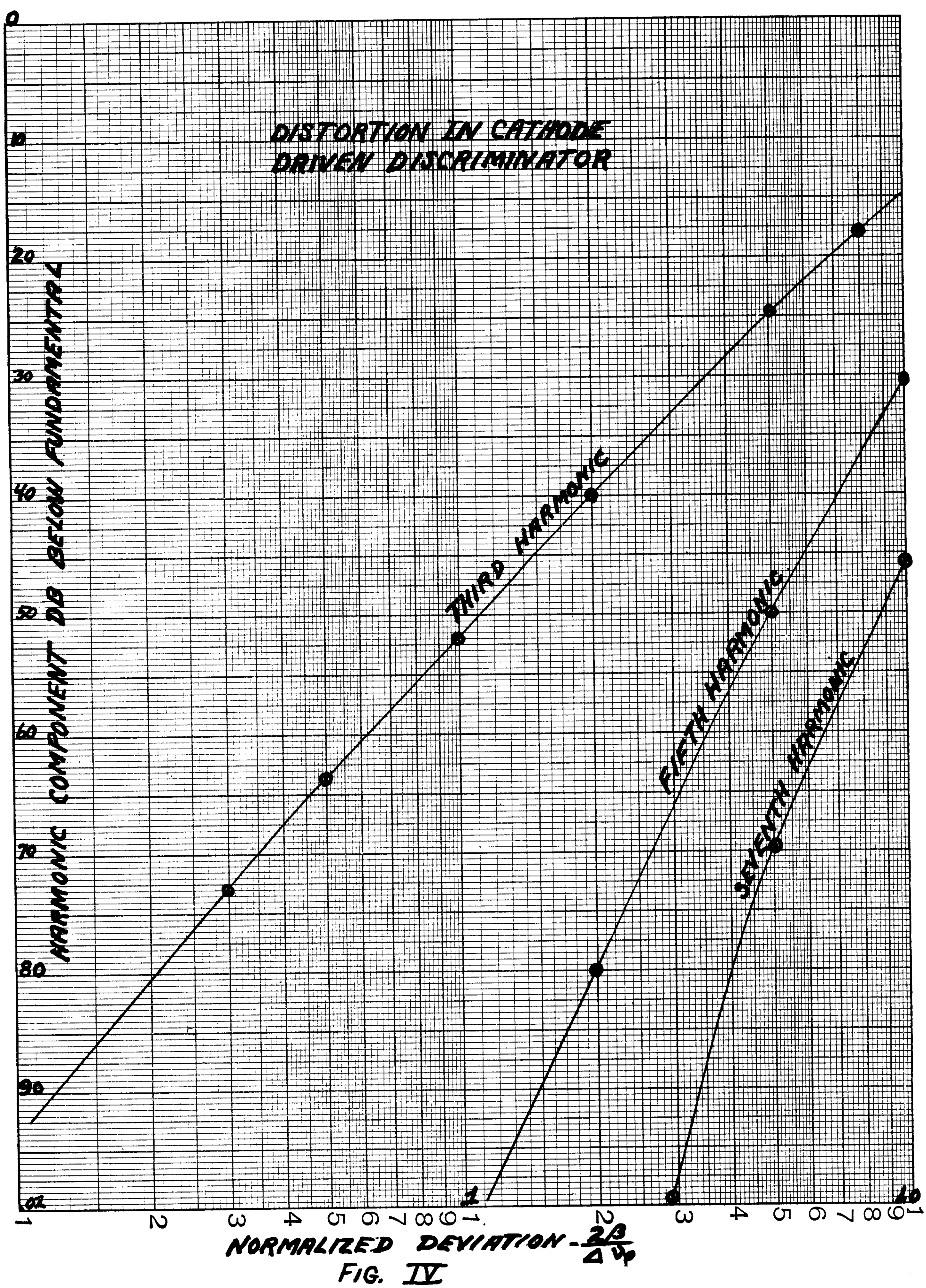

DISTORTION IN CATHODE DRIVEN DISCRIMINATOR
HARMONIC COMPONENT DB BELOW FUNDAMENTAL
THIRD HARMONIC
FIFTH HARMONIC
SEVENTH HARMONIC
NORMALIZED DEVIATION - $\frac{2\beta}{\Delta\nu_p}$

FIG. IV