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NRL REPORT 3998

R6667

HARMONIC DISTORTION IN AMPLIFIERS

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Radio Division

C18

June 17, 1952

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ABSTRACT

To correlate nonlinear distortion with the various parameters in vacuum-tube circuits and to determine methods for reducing this distortion, a theoretical analysis, supported by experimental measurement, was made of amplifier and cathode-follower circuits. The analysis shows that under certain operating conditions minimums may exist for the various harmonics in a vacuum-tube circuit. These minimums do not ordinarily occur for different harmonics under identical operating conditions. Although measurements were made using 6AK5 and 6C4 tubes at audio frequencies, the analysis is also valid for broadband amplifiers at higher frequencies. Curves obtained experimentally illustrate the relation between harmonic distortion and such parameters as plate voltage, grid bias, and load resistance. For a limited range of operating conditions, second- or third-harmonic distortion will drop from an average value of several percent to less than 0.01 percent.

PROBLEM STATUS

This is an interim report; work is being continued.

AUTHORIZATION

NRL Problem R09-51
RDB Project NE 091-035

Manuscript submitted May 12, 1952

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HARMONIC DISTORTION IN AMPLIFIERS

INTRODUCTION

In the more extensive receiver installations, especially at shore stations, the space limitations or losses in the long transmission lines can seriously impair the performance of the receiver system. One approach for improving the receiver system performance is the use of multicouplers, permitting the connection of several receivers to a common antenna and thus reducing the number of antennas required for any given installation.

Multicouplers have been divided into active and passive types. The passive-type multicoupler (1-4) uses only bilateral circuit elements and is suitable for both transmitter and receiver applications. The resonant circuit and bandpass types of multicouplers are in this category. The bandpass type, which is essentially a series of complementary filters, divides the frequency spectrum into a number of bands and allows only one equipment to operate in each band. In the resonant circuit type of multicoupler, each channel is tuned independently; this permits each equipment to operate at any frequency within the frequency limits of the system, provided the spacing between channels is greater than a specified minimum value.

The active type multicoupler (5-8) uses electron tubes or similar unilateral circuit elements and in general is limited to receiver applications. The basic circuit in this type of multicoupler is a broadband amplifier, such as the cathode follower. Maximum flexibility is provided, since each channel covers the frequency band and there is no restriction as to channel spacing. However, the problems of nonlinear distortion and generation of noise have imposed serious limitations on the usefulness of this type of multicoupler in some applications. The input to a multicoupler may consist of several simultaneous signals ranging in intensity from the order of one microvolt to several hundred thousand microvolts. The nonlinear distortion in the circuit should be so low that no interfering signals will be generated which have an intensity of the same order as the weakest signal to be received. Hence the undesired signals generated in the nonlinear circuits should, ideally, be 100 db or more below the strongest signal. This means that the percent distortion for this signal should be less than 0.001 percent.

The factors that must be considered in the design of the active type of receiver multicouplers are:

(a) Nonlinear distortion

(b) Signal-to-noise ratio

(c) Isolation

(d) Amplification

No extensive study has been made to determine how each of these factors varies with the parameters of a vacuum-tube circuit. If this information were available, it would be possible to predetermine the characteristics of any given multicoupler. The objective of this problem is to determine how the above-named factors vary with circuit parameters for typical amplifier and cathode-follower circuits that are suitable for multicoupler applications. This will also include the development of techniques for controlling or improving the performance characteristics of multicoupler circuits.

Nonlinear distortion and signal-to-noise ratio are the two most important factors to be considered. This report is concerned only with nonlinear distortion and in particular is restricted to harmonic distortion.

THEORETICAL ANALYSIS OF HARMONIC DISTORTION IN AMPLIFIERS

The analysis, design, and test of broadband amplifier and cathode-follower circuits for the 2 to 30 Mc band is time consuming because of a large number of secondary parameters, such as interelectrode capacity, distributed capacity, and lead inductance that must be taken into consideration. However, the effect of these secondary parameters is negligible in the vlf band, thus permitting a great simplification in the measurements. Performance characteristics of a simple amplifier or cathode-follower circuit having a resistive load in the vlf band are approximately equivalent to those of a well-designed broadband amplifier or cathode follower in the 2 to 30 Mc band.

The magnitude of the amplification (neglecting the phase reversal) of a simple resistance-coupled amplifier of low gain at audio frequencies is given by

$$A = \frac{\mu R_L}{r_p + R_L} \tag{1}$$

where μ is the amplification factor, r_p is the plate resistance, and R_L the load resistance (9). The total harmonic distortion will be zero only if the amplification is constant over the entire cycle of grid voltage, so that the incremental change in plate voltage is exactly proportional to the incremental change in grid voltage and the proportionality factor is a constant.

Harmonics of the input signal frequency will be generated in the amplifier if either μ or r_p is not constant over the entire cycle of grid voltage swing. Under these conditions the incremental change in plate voltage is not proportional to the incremental change in grid voltage. However, it is possible for one or more harmonics to be zero independently of the others. The attainment of constant proportionality between plate current and grid voltage is dependent upon tube design.

The instantaneous plate current in a vacuum tube can be expressed in the form of a Taylor series, such as

$$i_p = I_o + ae_c + be_c^2 + ce_c^3 + - - -, \tag{2}$$

where e_c is the instantaneous grid voltage and I_o, a, b, c are circuit constants. If the plate current is known at several values of grid bias along a given load line of resistance R_L, then I_o, a, b, c can be determined by solving simultaneous equations. The number of simultaneous equations needed will be the same as the number of terms used in Equation (2).

The grid voltage will generally contain both ac and dc components. In Equation (2) let

$$e_c = E_c + E_m \sin \omega t \qquad (3)$$

where E_c is the control grid dc voltage and $E_m \sin\omega t$ is the applied signal voltage. Then

$$\begin{aligned} i_p &= I_0 + a(E_c + E_m \sin\omega t) + b(E_c + E_m \sin\omega t)^2 + c(E_c + E_m \sin\omega t)^3 + \cdots \\ &= I_0 + aE_c + bE_c^2 + cE_c^3 + \tfrac{1}{2}bE_m^2 + \tfrac{3}{2}cE_cE_m^2 \\ &\quad + (a + 2bE_c + 3cE_c^2 + \tfrac{3}{4}cE_m^2)E_m \sin\omega t \\ &\quad - (\tfrac{1}{2}b + \tfrac{3}{2}cE_c)E_m^2 \cos 2\omega t \\ &\quad - (\tfrac{1}{4}c)E_m^3 \sin 3\omega t + \cdots \end{aligned} \qquad (4)$$

Only the first four terms of the power series will be considered here. Harmonics above the third will appear in Equation (4) if more terms are used in the Taylor series expansion.

These equations take into account the effect of the dc grid bias, which is not usually considered in this type of analysis. Thus the coefficients can be used over a considerable portion of a given load line as well as for a wide range of signal amplitudes.

The percent harmonic present in the plate current can be expressed as the ratio of the peak value of the harmonic to the peak value of the fundamental, hence the percent second harmonic is given by

$$d_2 = \frac{(b + 3cE_c)E_m}{2a + 4bE_c + 6cE_c^2 + \frac{3}{2}cE_m^2} \times 100 \qquad (5)$$

and the percent third harmonic by

$$d_3 = \frac{cE_m^2}{2(2a + 4bE_c + 6cE_c^2 + \frac{3}{2}cE_m^2)} \times 100. \qquad (6)$$

Equations (5) and (6) should not be used outside the range of the grid-bias voltages used in determining the constants. These equations will be more accurate if higher-order terms are added to the Taylor series expansion for i_p given in Equation (2). However, the accuracy obtainable is usually limited by the accuracy of the experimental data used in determining the constants in Equation (2).

It should be noted that the percent second harmonic is (to a good approximation) proportional to the ac signal amplitude and that the percent third harmonic is proportional to the square of the signal amplitude. Hence the actual arithmetic value of the second-harmonic voltage appearing in the output of a vacuum-tube circuit will be proportional to the square of the signal voltage, and the third-harmonic voltage proportional to its cube.

It may also be seen in Equations (5) and (6) for the percent second and third harmonic, respectively, that operating conditions may exist where the numerators of these equations are zero. If the numerator of Equation (5) is set equal to zero, then (neglecting the higer-order terms which will, in an actual case, be present to some extent) the second harmonic will be zero. In a similar manner, the third harmonic will be zero for the operating conditions that make the numerator of Equation (6) zero. These minimum distortion conditions need not lie within the useful operating range of a particular electron tube; it has simply been shown that they may exist. When the operating point passes a minimum distortion point for a particular harmonic, the sign of that harmonic changes and hence the harmonic undergoes a 180 degree phase shift. Negative percent distortion is, of course, impossible; the sign simply indicates the phase of the harmonic voltage.

If higher-order terms are considered, it will be seen that the operating conditions for a minimum in a particular harmonic are dependent upon the amplitude of the signal voltage. When the input voltage is a few tenths of a volt or more, a noticeable change may have to be made in at least one circuit parameter in order to maintain the conditions for a harmonic minimum when the signal level is changed. Hence it is evident that several more terms must be added to Equation (2) for a complete mathematical analysis of conditions for minimum distortion.

THEORETICAL ANALYSIS OF DISTORTION IN CATHODE FOLLOWERS

The equation for the amplification of an amplifier circuit (the conventional or grounded-cathode amplifier) with feedback is

$$A_a = \frac{A}{1 - \beta A} \tag{7}$$

where A is the magnitude of the amplification without feedback and is assumed to be a constant, and β is the ratio of the feedback voltage to the load voltage (10). In the case of a cathode-follower circuit or grounded-plate amplifier (Figure 1), β is minus one (11). Hence

$$A_a = \frac{A}{1 + A}. \tag{8}$$

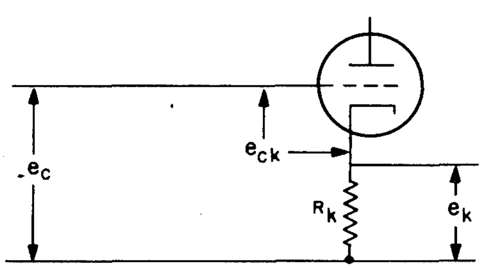

Figure 1 - Cathode-follower circuit

If it is assumed that there is no distortion in the feedback circuit, it can be shown (10) that the distortion in a cathode follower should be less than the distortion in a conventional amplifier under the same operating conditions by the factor (1 + A) when the output voltage is the same for both circuits.

In multicoupler applications, the comparison between amplifier and cathode follower should be made for the same input voltage instead of the same output voltage. In the design of multicouplers with low nonlinear distortion one is concerned primarily with the antenna voltages or multicoupler input voltages. The output signal level is important only in so far as it affects other factors such as noise ratio, isolation, and receiver input signal. Since the grid-to-cathode voltage is $1/(1 + A)$ of the input voltage and since the second-harmonic distortion is approximately proportional to the grid-to-cathode voltage, the second-harmonic distortion in a cathode follower is $1/(1 + A)^2$ of the value for an amplifier operating under the same conditions with the same input signal. Thus

$$D_2 = d_2 \frac{1}{(1 + A)^2} \qquad (9)$$

where D_2 is the percent second-harmonic distortion in a cathode follower and d_2 defined in Equation (5), is the percent second-harmonic distortion in an amplifier under the same operating conditions.

Since the third-harmonic distortion is approximately proportional to the square of the signal level in an amplifier, the third-harmonic distortion in a cathode follower under the same operating conditions will be

$$D_3 = d_3 \frac{1}{(1 + A)^3} \qquad (10)$$

where D_3 is the percent third-harmonic distortion in a cathode follower and d_3 is the percent third-harmonic distortion in an amplifier under the same operating conditions.

It must be emphasized that the above formulas for the reduction of distortion in cathode followers are based upon the assumption of no distortion in the feedback circuit. It is a difficult problem to keep the phase distortion low in a cathode follower operating over a wide frequency band. Thus the reduction in distortion in cathode followers that are used in multicoupler circuits in the high-frequency band may be much less than is indicated above.

Since there is some distortion in a cathode follower, the cathode current is not directly proportional to the grid voltage. The amplification varies along the load line and hence A in Equation (7) must be treated as a variable. As in the amplifier, the load current will be a function of the grid-to-cathode voltage. But in the case of the cathode follower, this is not identical to the input signal voltage. Following a procedure similar to that used for the amplifier, the cathode current is expressed in terms of grid-cathode voltage by

$$i_k = I_o + ae_{ck} + be_{ck}^2 + ce_{ck}^3 + de_{ck}^4 + - - - \qquad (11)$$

where e_{ck} is the instantaneous grid-cathode voltage and I_o, a, b, c, d are circuit constants.

From Figure 1 it is evident that

$$e_{ck} = e_c - R_k i_k . \qquad (12)$$

An expression for the load current in terms of input signal can now be obtained for the cathode follower. This will be similar to Equation (4) for the amplifier, and may be used to determine the percentage of the various harmonics in the cathode-follower output. It will be seen, by setting the numerators of the expressions for the various harmonics to zero, that minimums in the harmonics need not occur in the cathode follower under the same operating conditions as in the conventional amplifier, since the conditions for a harmonic minimum have changed. This will be considered further in the section on experimental measurement. The point to be emphasized here is that prediction of the amount of distortion reduction in a cathode follower by the factor $1/(1 + A)$ is not reliable when attempting to secure extremely low values of distortion.

EXPERIMENTAL ANALYSIS

Experimental measurements of harmonic distortion were made, using the setup shown in Figure 2, with a fundamental signal at a fixed frequency of 5 kc. A narrow-bandpass filter, centered at 5 kc, was placed across the output of the signal generator to greatly suppress the harmonics present in its output. Harmonics from the signal source will cause erroneous results unless their magnitude is considerably less than that being measured. Hence the percent harmonic at the filter output, when connected to the measuring equipment, should be less than the lowest value of harmonic to be measured (or at least so small that it gives no reading on the measuring equipment).

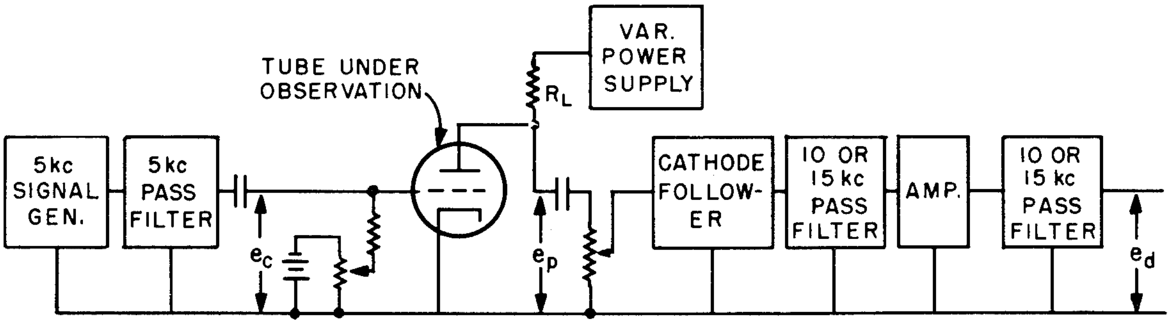

Figure 2 - Simplified diagram of distortion-measuring setup

Means were provided for varying the circuit parameters, such as grid bias, plate voltage, load resistance, and screen voltage (in the case of pentodes) for the tube under observation. The filament voltage was maintained at its rated value. The resistor in the grid circuit had a resistance of 10,000 ohms.

The output of the tube being investigated must be coupled to a low-impedance filter through a device having a high-impedance input and producing little distortion. A cathode follower appeared to be the best answer, since it has a high-impedance input, a low-impedance output, and can be made to produce very little distortion. The harmonic distortion produced in the cathode follower was kept low by using a small input signal and by using a high cathode resistance, thus producing a large amount of negative feedback. The filter was needed to greatly attenuate the fundamental so that harmonics produced in the amplifier following it would be negligible and also to attenuate all except the desired harmonic. Suppression of undesired signals was on the order of 100 db.

In order to determine the percent distortion, the amplification of the circuit following the tube under observation must be measured. The maximum amplification obtainable with the equipment used was somewhat over 60 db.

Percent harmonic is defined as

$$\frac{\text{harmonic voltage}}{\text{fundamental voltage}} \times 100.$$

The percent distortion actually measured was more nearly

$$\frac{\text{harmonic voltage}}{\sqrt{(\text{fund. volt.})^2 + (\text{harm. volt.})^2}} \times 100$$

but the error is small if the distortion is less than about ten percent.

The measurements were made at audio frequencies in order to greatly reduce the effects of stray capacitance. It was found that the original measuring circuit, using a vacuum-tube voltmeter for measuring distortion, was not capable of measuring values of distortion below several hundredths of a percent due to distortion in the cathode follower and noise in the amplifier. Noticeable improvement was obtained by further reducing the input voltage to the cathode follower and by employing a G.R. 736-A Wave Analyzer for measuring the harmonic voltage.

EXPERIMENTAL RESULTS

A better understanding of nonlinear distortion in electron tube circuits may lead to methods and techniques for improving this characteristic in multicoupler circuits. The experimental data has been collected for the purpose of increasing the information on non-linear distortion without considering detailed design factors for multicouplers. Hence measurements have been limited to a typical triode, the 6C4, and a typical pentode, the 6AK5.

A number of curves are included here to illustrate the effect of the circuit parameters on the percentage of the various harmonics in the output from a vacuum-tube amplifier. Several minimum points, resulting from a phase reversal of the harmonic voltage, will be found in these curves.

Harmonic distortion is a function of tube construction and operating conditions. A few general rules could be given, but a more detailed analysis is necessary if conditions for extremely low values of distortion are to be obtained.

Input signals of 0.5 and 1.0 volt rms were used for convenience in measuring distortion. Since it is known that the percent second harmonic is very nearly proportional to the input voltage and the percent third harmonic to the square of the input, the distortion can be easily calculated for signals which are greater or smaller than those used in the measurements. The accuracy of this approximation will decrease as the signal increases, especially if grid current flows or the tube is driven to cutoff.

Pentode Amplifier

Second Harmonic – A comparison of measured and calculated values of second-harmonic distortion in a 6AK5 amplifier will be found in Figure 3. The point of minimum distortion was calculated to occur at a plate voltage of 60 volts, but the measured curve indicates that the minimum point occurs with a plate voltage of 72 volts. This agreement is as good as can be expected, since the degree of nonlinearity under consideration is small and the analytical means are subject to errors in the measurement of circuit parameters, particularly plate current.

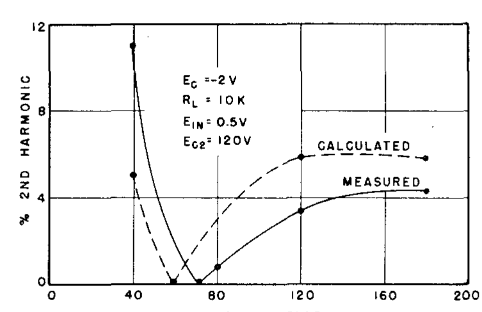

Figure 3 - Comparison of measured and calculated values of second-harmonic distortion in 6AK5 as amplifier

Figure 4, which shows the effect of plate voltage on the second harmonic, indicates that minimums may be obtained with a number of different sets of circuit parameters. The value of the distortion at the minimums should, within the accuracy of the mathematical analysis, be zero with a resistive load. The actual value which is attainable is not known since, due to noise and distortion in the system, the measuring equipment was not reliable when the distortion to be measured was below a few hundredths of a percent. With the circuit and frequencies used in the measurements, the harmonic distortion was below this value in many cases, so that it can be said that a reduction on the order of 30 to 40 db or more from the average value is often possible by operating at a minimum.

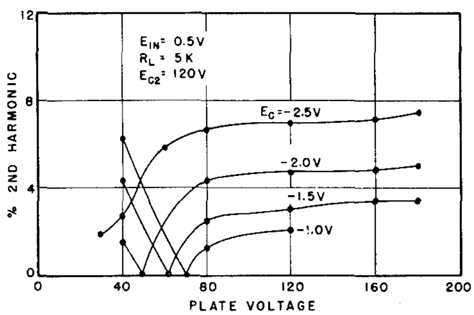

Figure 4 - Measured second-harmonic distortion vs. plate voltage in 6AK5 as amplifier

The locus of second-harmonic minimums in a 6AK5 amplifier is shown in Figure 5. Due to a variety of factors, some of these operating conditions will be more desirable than others. For low values of load resistance they occur at very low plate voltages and are quite critical with respect to operating conditions.

Figure 6 shows that the percent harmonic in a 6AK5 is very nearly proportional to the magnitude of the input signal for signals less than about one volt rms. This is in agreement with the theoretical analysis.

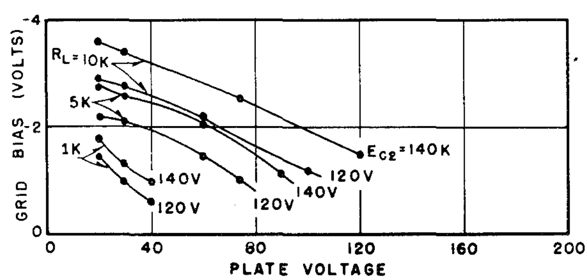

Figure 5 - Measured locus of second-harmonic minimums in 6AK5 as amplifier

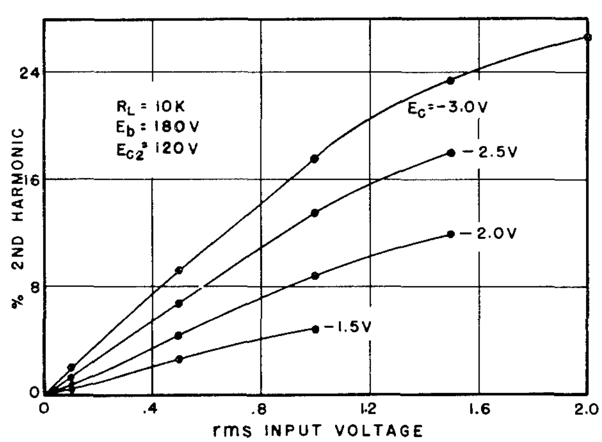

Figure 6 - Measured second-harmonic distortion vs. input voltage in 6AK5 as amplifier

Third Harmonic - Under certain operating conditions there will be minimums in the third harmonic in a 6AK5 amplifier. The locus of these minimums is illustrated in Figure 7. They are practically independent of plate voltage for high values of voltage and in the same region are also only slightly dependent upon the value of load resistance. The minimums permit a reduction of the third-harmonic distortion on the order of 40 db from the average value, the actual amount of reduction not being known due to limitations in the measuring circuit. But they occur at relatively large values of grid bias which border on the useful range and for which the second harmonic is quite large. By comparison with Figure 5 it is evident that second-harmonic and third-harmonic minimums do not generally occur under identical operating conditions.

The third harmonic in the 6AK5 is fairly independent of the load at low values of resistance and, except for the region near the minimums, its magnitude is generally on the order of several percent with a 0.5 volt input signal.

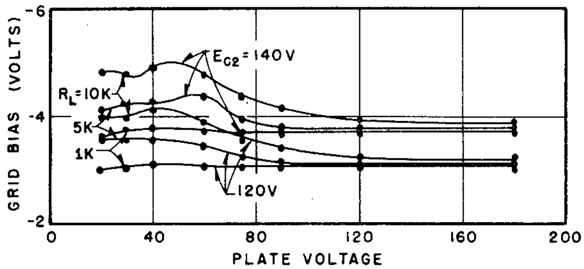

Figure 7 - Measured locus of third-harmonic minimums in 6AK5 as amplifier

Triode Amplifier

Second Harmonic - The characteristic curves of the 6C4 would seem to indicate that it is capable of very linear amplification. But measured values of second-harmonic distortion for a 1.0-volt input signal were generally on the order of a few percent, very much greater than that desirable in a receiver multicoupler. No points of minimum distortion were found, and hence it must be concluded that the minimum points predicted in the theory did not occur within the useful operating range of the tube.

The second harmonic in the 6C4 can be reduced by decreasing the bias voltage and increasing the plate voltage, but a limitation is imposed on this method of distortion reduction by the current and voltage ratings of the tube.

Third Harmonic - The variation of the percent third harmonic with respect to plate voltage for a 6C4 is shown in Figure 8. The minimums predicted in the theory are seen to be present in these curves, permitting a relatively large reduction of the third-harmonic distortion. The conditions for a minimum are dependent upon a number of circuit parameters, the effect of some of which can be seen from the curves. Although a reduction in the third harmonic on the order of 40 db or more can be obtained at one of the minimum points, the percent second harmonic may be very large under the same operating conditions.

The third harmonic, in general, tends to decrease with an increase in load resistance, as can be seen in Figure 9. Under other operating conditions the minimums will occur at values of plate load different from those indicated in these curves.

Cathode Follower

Using the method suggested by Shapiro (12), the feedback network in a cathode-follower circuit can be considered as a part of the tube characteristic and a dynamic operating curve can be obtained for the cathode follower (Figure 10). By comparison with the characteristic for a conventional amplifier (also shown in Figure 10) it will be seen that the path of operation of the cathode follower is considerably more linear than that of an amplifier operated under the same conditions. A more careful examination will show that the curvature of the cathode-follower characteristic is not a simple function of that for an amplifier, indicating that the reduction in distortion need not be exactly that indicated by the customary feedback analysis.

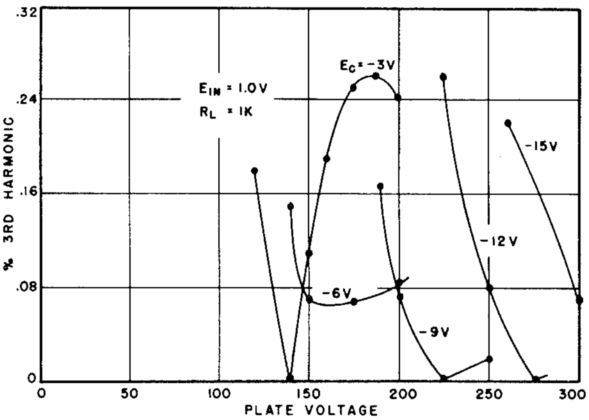

Figure 8 - Measured third-harmonic distortion vs. plate voltage in 6C4 as amplifier

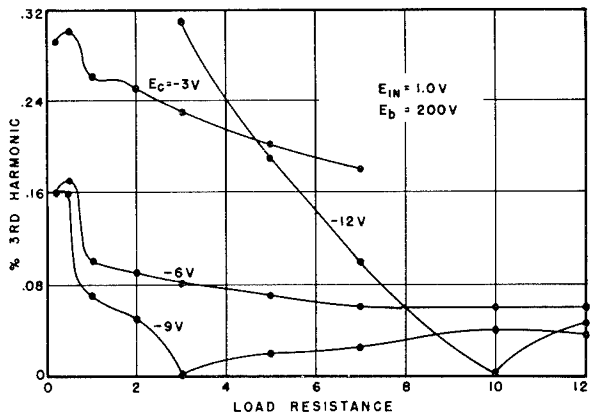

Figure 9 - Measured third-harmonic distortion vs. load resistance in 6C4 as amplifier

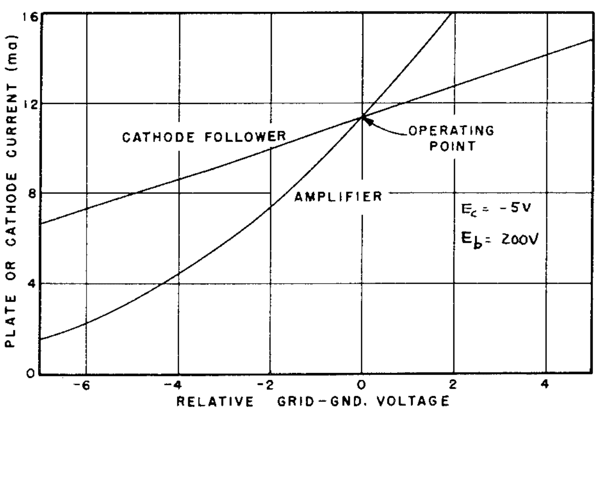

Figure 10 - Dynamic characteristics of 6C4 with 1000-ohm load

Figures 11 and 12 illustrate the minimums which were found for the third harmonic with a 6C4 in a cathode-follower circuit. These figures may be considered as views in two perpendicular planes of a three-dimensional characteristic. The curves of Figure 12 represent the locus of minimum points and are not obtained directly from Figure 11 (except for a few common points). The curve for 3-volt bias is the only one which closely agrees with the simple form of the theoretical prediction of distortion reduction due to feedback in which A is considered as a constant.

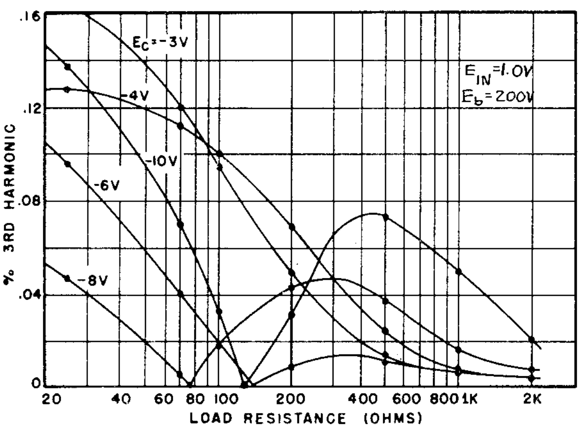

Figure 11 - Measured third-harmonic distortion in 6C4 as cathode follower

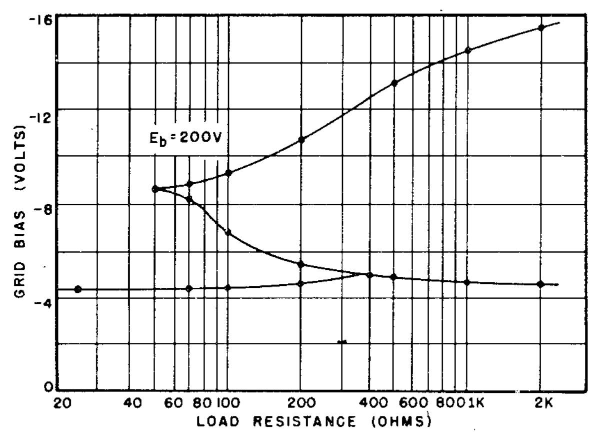

Figure 12 - Measured locus of third-harmonic minimums in 6C4 as cathode follower

The minimums in the cathode follower occured under conditions appreciably different from those in an amplifier, indicating that the previous statements concerning a comparison of the dynamic operating curves are correct. This is also in agreement with the predictions of the mathematical analysis in the theory. Hence is must be concluded that circuit parameters which give extremely low values of distortion in an amplifier will not necessarily bring about optimum results in a cathode follower.

CONCLUSIONS

In order to reduce the nonlinear distortion to the very low values required in multicouplers, it will probably be necessary to use a combination of several techniques. As a result of the investigation to date, it can be concluded that:

a. The second-harmonic distortion in an amplifier can be reduced by 40 db or more by selecting the values of load resistance, grid bias, and plate voltage that give minimum second-harmonic distortion in certain tubes.

b. The third-harmonic distortion in an amplifier can be reduced by 40 db or more by selecting the values of circuit parameters corresponding to the minimum distortion conditions in certain tubes.

c. The operating conditions for minimum values of second- and third-harmonic distortion are not the same, do not necessarily occur within the useful operating range of a particular tube, and may be quite critical with respect to certain circuit parameters.

d. The operating conditions for minimum distortion are a function of the amplitude of the input signal.

e. The minimum values in the harmonic distortion are also present in cathode-follower circuits, but do not necessarily occur under the same operating conditions as in an amplifier since the ordinary feedback analysis where A is considered constant may not be valid.

f. The percentage second-harmonic distortion is approximately proportional to the input signal.

g. The percentage third-harmonic distortion is approximately proportional to the square of the input signal.

h. The percentage second-harmonic distortion in a cathode follower is approximately $1/(1 + A)^2$ of the value for the amplifier without feedback and having the same input signal, where A is the amplification without feedback. This assumes that there is no distortion in the feedback circuit and that A is a constant.

i. The percentage third-harmonic distortion in a cathode follower is approximately $1/(1 + A)^3$ of the value for the amplifier having the same input signal without feedback, assuming zero distortion in the feedback circuit and a constant A.

j. The distortion in the feedback circuit of a cathode follower must be kept low over the operating frequency band.

Finally, it may be said that a push-pull amplifier or cathode follower with the operating conditions corresponding to the minimum value of the third-harmonic distortion may be effective in reducing harmonic distortion.

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Naval Research Laboratory. Report 3998. HARMONIC DISTORTION IN AMPLIFIERS, by S. R. Swanson and W. G. Long, Jr. 13 pp. & figs., June 17, 1952.

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Naval Research Laboratory. Report 3998. HARMONIC DISTORTION IN AMPLIFIERS, by S. R. Swanson and W. G. Long, Jr. 13 pp. & figs., June 17, 1952.

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2. Cathode followers – Circuits – Distortion

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-- 1 OF 1
-- 1 - AD NUMBER: B200361
-- 2 - FIELDS AND GROUPS: 9/1
-- 3 - ENTRY CLASSIFICATION: UNCLASSIFIED
-- 5 - CORPORATE AUTHOR: NAVAL RESEARCH LAB WASHINGTON DC
-- 6 - UNCLASSIFIED TITLE: HARMONIC DISTORTION IN AMPLIFIERS.
-- 8 - TITLE CLASSIFICATION: UNCLASSIFIED
--10 - PERSONAL AUTHORS: SWANSON, S. R.; LONG, W. G.
--11 - REPORT DATE: 17 JUN 1952
--12 - PAGINATION: 17P MEDIA COST: $ 7.00 PRICE CODE: AA
--14 - REPORT NUMBER: NRL-3998
--18 - MONITOR ACRONYM: XB
--19 - MONITOR SERIES: NRL
--20 - REPORT CLASSIFICATION: UNCLASSIFIED
--22 - LIMITATIONS (ALPHA): DISTRIBUTION: DTIC USERS ONLY.
--23 - DESCRIPTORS: *HARMONICS, *DISTORTION, *AMPLIFIERS, FREQUENCY,
-- MEASUREMENT, RESISTANCE, THEORY, GRIDS, NONLINEAR SYSTEMS, THIRD
-- HARMONIC GENERATION, BROADBAND, ELECTRON TUBES, CIRCUITS, BIAS,
-- AUDIO FREQUENCY.
--24 - DESCRIPTOR CLASSIFICATION: UNCLASSIFIED
--25 - IDENTIFIERS: VACUUM TUBE CIRCUITS
--26 - IDENTIFIER CLASSIFICATION: UNCLASSIFIED
--27 - ABSTRACT: TO CORRELATE NONLINEAR DISTORTION WITH THE VARIOUS

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-- PARAMETERS IN VACUUM-TUBE CIRCUITS AND TO DETERMINE METHODS FOR
-- REDUCING THIS DISTORTION, A THEORETICAL ANALYSIS, SUPPORTED BY
-- EXPERIMENTAL MEASUREMENT, WAS MADE OF AMPLIFIER AND CATHODE-
-- FOLLOWER CIRCUITS. THE ANALYSIS SHOWS THAT UNDER CERTAIN OPERATING
-- CONDITIONS MINIMUMS MAY EXIST FOR THE VARIOUS HARMONICS IN A
-- VACUUM-TUBE CIRCUIT. THESE MINIMUMS DO NOT ORDINARILY OCCUR FOR
-- DIFFERENT HARMONICS UNDER IDENTICAL OPERATING CONDITIONS. ALTHOUGH
-- MEASUREMENTS WERE MADE USING 6AK5 AND 6C4 TUBES AT AUDIO
-- FREQUENCIES, THE ANALYSIS IS ALSO VALID FOR BROADBAND AMPLIFIERS AT
-- HIGHER FREQUENCIES. CURVES OBTAINED EXPERIMENTALLY ILLUSTRATE THE
-- RELATION BETWEEN HARMONIC DISTORTION AND SUCH PARAMETERS AS PLATE
-- VOLTAGE, GRID BIAS, AND LOAD RESISTANCE. FOR A LIMITED RANGE OF
-- OPERATING CONDITIONS, SECOND- OR THIRD-HARMONIC DISTORTION WILL
-- DROP FROM AN AVERAGE VALUE OF SEVERAL PERCENT TO LESS THAN 0.01
-- PERCENT.
--28 - ABSTRACT CLASSIFICATION: UNCLASSIFIED
--29 - INITIAL INVENTORY: 1
--33 - LIMITATION CODES: 12
--35 - SOURCE CODE: 251950
--36 - ITEM LOCATION: DTIC
--40 - GEOPOLITICAL CODE: 1101
--41 - TYPE CODE: N

AD-B800 792 AD-B200361

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ATI 165 384 (Copies obtainable from ASTIA-DSC)

Office of Naval Research, Naval Research Lab., Wash., D.C. (NRL Report 3998)

EO 10501 dd 5 NOV 1953

Harmonic Distortion in Amplifiers

Swanson, S.R.; Long, W.G., Jr. 17 June'52 13pp. diagrs, graphs

Signals - Distortion
Amplifiers
Circuits, Cathode follower

Electronics (3)
Communications (1)

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