DISTORTION REDUCTION IN AMPLIFIERS

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CONTENTS

ABSTRACT

In order to cause no interference to reception, the harmonic and intermodulation distortion produced in a receiver multicoupler must be below the noise level of the receivers. This means that the distortion must be below a level of about one microvolt, regardless of input-signal amplitude.

Several methods of reducing distortion in broadband amplifiers have been investigated with the aim of obtaining the desired reduction in distortion. These include push-pull operation, operation at a point of minimum distortion, and the use of feedback. Push-pull operation can be used to reduce even-order distortion by 20 to 30 db or more if the circuit is carefully balanced, but it alone is not capable of producing the desired freedom from distortion. Operation at a point of minimum distortion can result in considerable reduction of a given distortion term, but the results are critical with respect to operating conditions. Feedback is effective in reducing all types of distortion. However, the use of large amounts of negative feedback in r-f amplifiers is difficult and will require further study.

PROBLEM STATUS

This is an interim report; work on the problem is continuing.

AUTHORIZATION

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DISTORTION REDUCTION IN AMPLIFIERS

INTRODUCTION

The operation of a number of receivers from a common antenna is desirable at many receiving installations and may be accomplished by the use of a receiver multicoupler. In passive multicouplers a compromise must be made between signal-to-noise ratio and isolation between receivers, while in multicouplers using vacuum tubes the necessary isolation can be obtained with little loss in signal-to-noise ratio. However, the nonlinear characteristics of vacuum tubes produce interference to reception and have imposed a limitation on the usefulness of active-type multicouplers. Nonlinear distortion produced in broadband vacuum-tube amplifiers is of three principal types: harmonic, intermodulation, and cross modulation. Factors affecting the magnitude of these types of distortion have been considered in previous reports (1,2).

At least three methods are available for obtaining low distortion from a given tube type. These include the use of feedback, operation at a point of minimum distortion, and push-pull operation. Since push-pull amplifiers have less even-order distortion than single-ended circuits of similar design, their use would seem desirable in circuits requiring low values of distortion. Push-pull cancellation of even-order distortion is the primary subject of this report, although other means of distortion reduction are also considered.

PERMISSIBLE DISTORTION

The work to date on this problem has indicated that nonlinear distortion created by electron tubes is the most serious factor limiting the usefulness of active-type receiver multicouplers. Accordingly, stress has been placed upon methods and techniques for reducing nonlinear distortion to an acceptable level.

There are at least three possible ways for stating the distortion characteristics necessary in a receiver multicoupler which will not degrade the performance of the over-all receiving system:

1. No distortion and hence no spurious responses

2. Distortion below that produced by the receivers

3. Harmonics and intermodulation below the noise level of the receivers

The first is an ideal case, since there will always be some distortion in a practical circuit using vacuum tubes.

The specifications for the second type of multicoupler will vary considerably if different types of receivers are used and will be a function of the frequency of the interfering signal or signals as well as the frequency to which the receiver is tuned. Hence the limitation on distortion will be considerably more severe in some cases than in others, so that the permissible distortion is difficult to determine.

The third is the more absolute measurement of a multicoupler's performance and will approach the performance of an ideal multicoupler. The limitations on the allowable distortion are more clearly defined than in the second case since the sensitivity of most communication receivers is known to be on the order of a few microvolts, so that the noise level will generally be on the order of one microvolt. Thus, for no noticeable distortion, harmonic and intermodulation distortion voltages must be below a level on the order of one microvolt. Cross modulation will be negligible if it is below a few percent. This condition will generally be fulfilled when harmonic and intermodulation distortion is low.

Figure 1 illustrates the relationship between distortion and signal amplitude. The distortion is also given in decibels below 100 percent. The solid sloping lines represent constant distortion voltage, so that the degree of distortion which will produce a given distortion voltage with a known input signal can be easily determined. The dashed line represents the normal relationship between second-harmonic distortion (or second-order intermodulation produced by two equal input signals) and signal amplitude, while the dotted line represents the normal relationship between third-harmonic distortion (or third-order intermodulation produced by two equal signals) and signal amplitude. The lines for second- and third-order distortion in an actual case will be parallel to the ones shown in the examples in Fig. 1. The figure may be extended if information is desired at other input signal or distortion levels. However, the curves of second- and third-harmonic distortion are approximate and hence may not be accurate at large signal levels. A gain of unity has been assumed in the multicoupler. If the gain is other than unity, the distortion voltage must be multiplied by this gain.

In order to demonstrate the degree of linearity needed in a multicoupler in terms of percent harmonic distortion, consider its use with a receiver having a noise level equivalent to 1.0 microvolt. For no apparent distortion in this system from a 1-millivolt signal, the percent 2nd, 3rd, 4th, etc, harmonics must be below 0.1 percent of 1 millivolt; for a 100-millivolt signal they must be below 0.001 percent, and so forth, as shown by the 1.0-microvolt line in Fig. 1. The percent distortion permissible for no interference decreases as the signal level increases, while in a practical circuit the percent distortion tends to increase with increased signal amplitude.

If the percent second-harmonic distortion of a particular vacuum-tube multicoupler is known for a given value of input-signal amplitude, the maximum signal which will produce no noticeable distortion can then be determined since the percent second harmonic is approximately proportional to the signal amplitude (1). If 1-percent distortion is produced by a 1-volt signal, a 10-millivolt signal will produce a second-harmonic voltage of 1 microvolt, as shown by the dashed line in Fig. 1. Similar lines can be drawn for other cases where the percent second-harmonic distortion is known for a given input amplitude.

In a similar manner, the signal amplitude producing a third-harmonic voltage of 1 microvolt can be found if the percent third-harmonic distortion is known for some signal amplitude, since the percent third harmonic is approximately proportional to the square of the signal amplitude (1). In the example shown by the dotted line in Fig. 1, the third harmonic is 0.1 percent for a 1-volt signal, so that 1 microvolt distortion will be produced with a 0.1-volt signal. Other curves of percent third harmonic vs. input signal will be parallel to the one shown in the example.

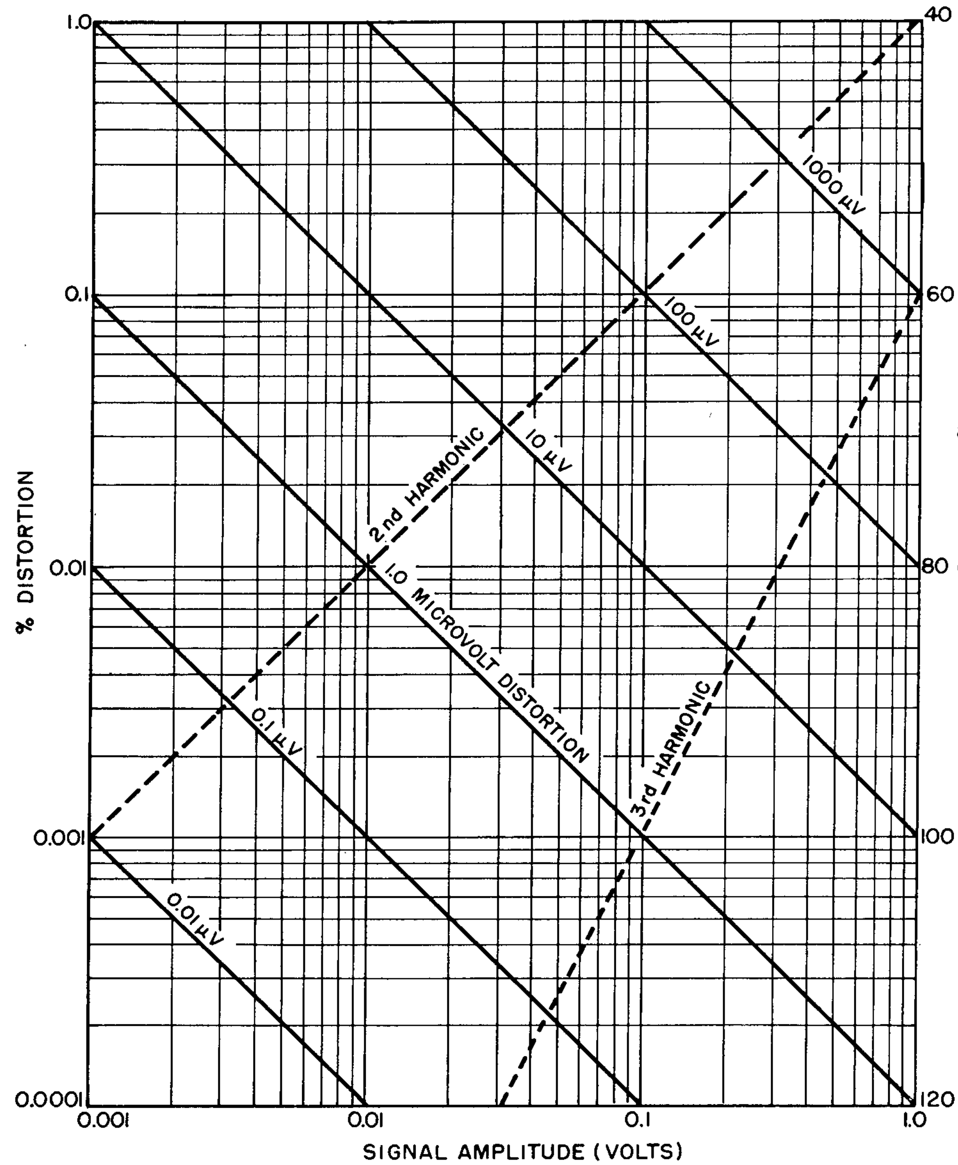

Fig. 1 - Distortion voltage as a function of signal amplitude and percent distortion

For two equal input signals, curves of intermodulation will be similar to those shown for harmonic distortion, except that the distortion voltages will be somewhat greater in magnitude than the harmonics of the same order (2). The curves in Fig. 1 are not applicable for two unequal signals, since the distortion will then be proportional to the product of the amplitudes, or powers of the amplitudes, of the input signals.

CANCELLATION OF EVEN-ORDER DISTORTION IN PUSH-PULL CIRCUITS

Push-pull amplifier circuits are widely used because the even-order distortion which they produce is considerably less than that produced in a single amplifier tube. If the characteristics of both tubes in a push-pull amplifier are identical (but not necessarily linear) the even-order distortion terms will cancel, so that all even-order harmonic and intermodulation terms in the output are zero. This cancellation can be complete only if the two sides of the push-pull amplifier are identical, so that the distortion voltages are exactly in phase and of equal magnitudes. Odd-order distortion terms will add, so that the percent odd-order distortion will be the same for both single and push-pull circuits if the input voltages to the tubes are equal.

Complete cancellation of even-order distortion in a push-pull circuit is impossible in practice. The amount of even-order distortion in the output will depend upon the difference in the characteristics of the tubes and other circuit elements as well as dissymmetry in the loads. If the voltages of a particular component of distortion are in phase but of different amplitude, the net distortion voltage will be equal to the difference in amplitude.

If the harmonic or intermodulation voltages appearing on the two sides of a push-pull amplifier are not in phase, the net distortion will be dependent upon this phase difference. The phase angle of a particular even-order distortion component produced on one side of a push-pull amplifier may be different from that on the other side if either the tube plate resistances or load impedances are different; hence the distortion may be a function of frequency.

In general, the magnitude of the difference voltage E_d is given by

$$E_d = E_1 \angle\theta_1 - E_2 \angle\theta_2 = \sqrt{E_1^2 + E_2^2 - 2E_1E_2\cos\theta_d} \qquad (1)$$

where E_1 and E_2 are the voltages of a particular distortion term appearing on the two sides of the output of a push-pull circuit and having phase angles θ_1 and θ_2 (with respect to the same reference); θ_d is the phase angle between the distortion components E_1 and E_2 and is equal to $\theta_2 - \theta_1$. The ratio of the distortion voltage E_d to the distortion voltage E_1 of one amplifier tube is shown vs. phase angle in Fig. 2 for various ratios of E_2 to E_1.

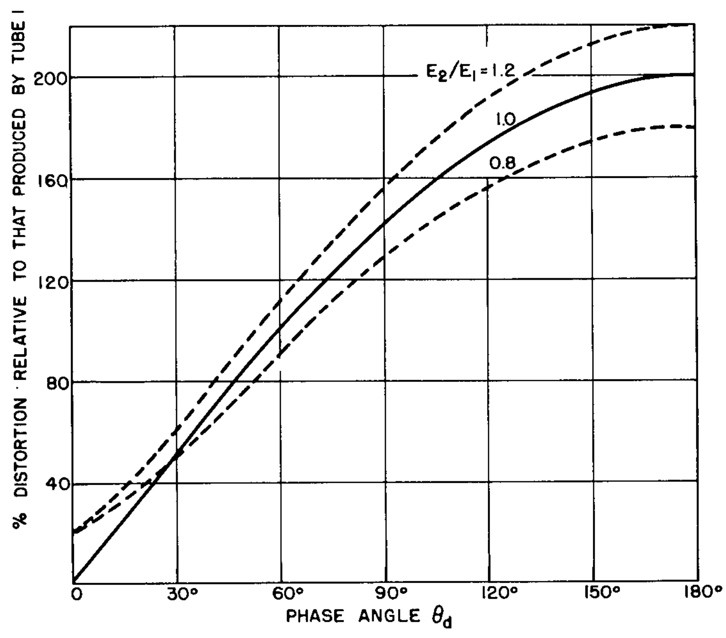

Fig. 2 - Percent even-order distortion in push-pull amplifier relative to that of single tube as a function of amplitude and phase difference

For small signals, the percent second harmonic produced by a single amplifier with low load impedance can be expressed as

$$d_2 = \frac{\frac{\partial g_m}{\partial E_c} E_m}{4 g_m} \times 100 \qquad (2)$$

where E_m is the peak value of the input voltage, E_c is the grid bias, and g_m is the transconductance. The second harmonic distortion in a push-pull circuit will be dependent upon the difference between the second-harmonic distortions produced in the two sides of the circuit. If the transconductance of one tube of the push-pull circuit is g_{m1} and that of the other is $g_{m2} = g_{m1} + \Delta g_{m1}$, then, assuming $(\partial g_{m2})/(\partial E_c) = (\partial g_{m1})/(\partial E_c)$ and no phase error, the percent second-harmonic distortion in the output will be

$$d_2' = \left[\frac{\frac{\partial g_{m1}}{\partial E_c} E_m}{4 g_{m1}} - \frac{\frac{\partial g_{m1}}{\partial E_c} E_m}{4(g_{m1} + \Delta g_{m1})}\right] \times 100$$

$$= \frac{\frac{\partial g_{m1}}{\partial E_c} E_m}{4 g_{m1}} \left[\frac{\Delta g_{m1}}{g_{m1} + \Delta g_{m1}}\right] \times 100. \qquad (3)$$

The ratio of the second harmonic produced in the push-pull circuit to that produced by the tube having transconductance g_{m1} is

$$\frac{d_2'}{d_2} = \frac{\Delta g_{m1}}{g_{m1} + \Delta g_{m1}} = \frac{\frac{\Delta g_{m1}}{g_{m1}}}{\frac{\Delta g_{m1}}{g_{m1}} + 1} \doteq \frac{\Delta g_{m1}}{g_{m1}} \qquad (4)$$

If the transconductances of the two tubes, as well as the partials with respect to E_c, are not equal, so that $g_{m2} = g_{m1} + \Delta g_{m1}$ and $(\partial g_{m2})/(\partial E_c) = (\partial g_{m1})/(\partial E_c) + \Delta(\partial g_{m1})/(\partial E_c)$, then the percent second harmonic will be

$$d_2' = \left[\frac{\frac{\partial g_{m1}}{\partial E_c} E_m}{4 g_{m1}} - \frac{\left(\frac{\partial g_{m1}}{\partial E_c} + \Delta \frac{\partial g_{m1}}{\partial E_c}\right) E_m}{4(g_{m1} + \Delta g_{m1})}\right] \times 100$$

$$= \left[\frac{\frac{\partial g_{m1}}{\partial E_c} \frac{\Delta g_{m1}}{g_{m1}} E_m - \Delta \frac{\partial g_{m1}}{\partial E_c} E_m}{4(g_{m1} + \Delta g_{m1})}\right] \times 100. \qquad (5)$$

The ratio of second harmonic in a push-pull circuit to that in a single tube is then

$$\frac{d_2'}{d_2} = \frac{\frac{\Delta g_{m1}}{g_{m1}} - \frac{\Delta \frac{\partial g_{m1}}{\partial E_c}}{\frac{\partial g_{m1}}{\partial E_c}}}{1 + \frac{\Delta g_{m1}}{g_{m1}}} \qquad (6)$$

These approximations are useful only when the load impedance is low, so that $Z_L \ll r_p$. Under these conditions the amplification is a function of g_m rather than of r_p and μ, which is generally a valid approximation in broadband amplifiers.

Figure 3 shows the percent second-order distortion from a push-pull amplifier with respect to that of tube No. 1 alone vs. the difference in tube characteristics represented by the ratio $[\Delta(\partial g_{m1})/(\partial E_c)]/[(\partial g_{m1})/(\partial E_c)]$. As an example of the use of Fig. 3, suppose that $(\partial g_{m2})/(\partial E_c)$ is 5 percent greater than $(\partial g_{m1})/(\partial E_c)$; thus $[\Delta(\partial g_{m1})/(\partial E_c)]/[(\partial g_{m1})/(\partial E_c)] = 0.05$. Also assume that g_{m2} is 10 percent greater than g_{m1}, so that $(\Delta g_{m1})/(g_{m1}) = 0.1$. From Fig. 3 it can be seen that for these conditions the percent second-harmonic distortion in the push-pull circuit relative to that produced by tube 1 alone is 13.3 percent.

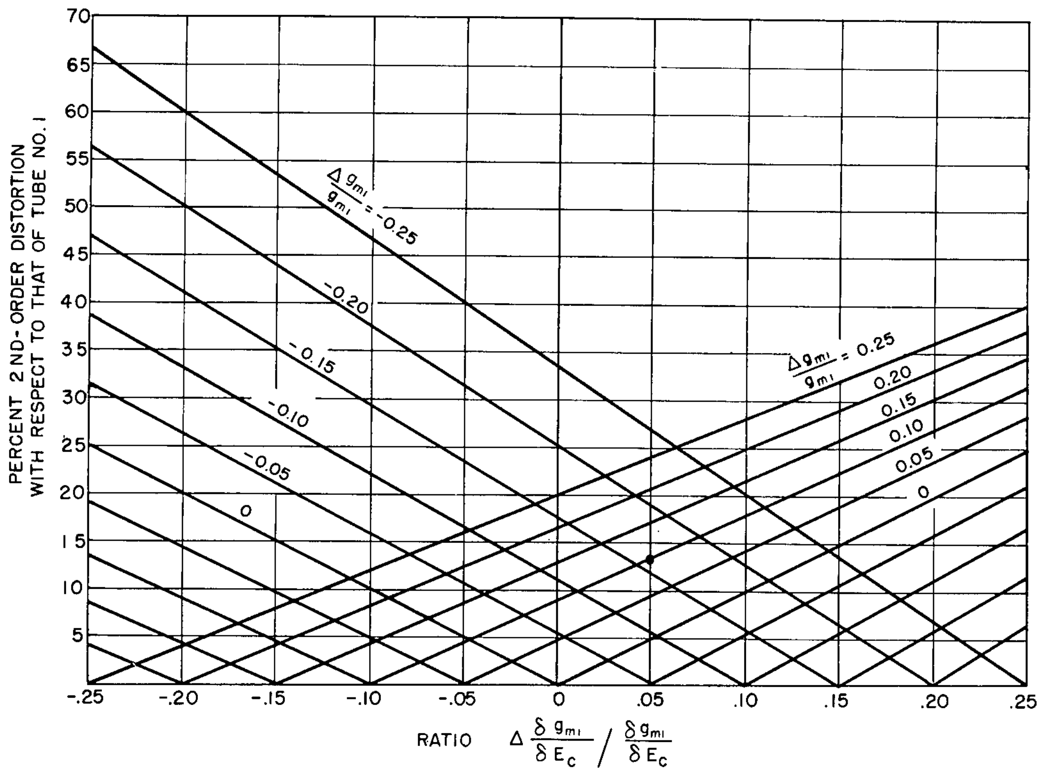

Fig. 3 - Percent second-order distortion in push-pull amplifier relative to that of single tube as a function of difference in tube characteristics

The percent fourth-harmonic distortion in a vacuum-tube amplifier can be expressed approximately as

$$d_4 = \frac{\frac{\partial^3 g_m}{\partial E_c^3} E_m^3}{32 g_m} \times 100 \qquad (7)$$

Hence a difference in the transconductance of the tubes will have the same effect upon the fourth harmonic as on the second, and a difference in the third partial of g_m with respect to E_c will have the same effect upon the fourth harmonic that a difference in the first partial has upon the second harmonic. The effect on intermodulation terms will be the same as on the corresponding harmonics.

EFFECT OF GRID BIAS ON DISTORTION MINIMUMS

With all circuit parameters fixed except the grid voltage, the percent third-harmonic distortion produced in a vacuum-tube amplifier can be expressed, by expansion of the method of Ref. 1, pp. 2-3, as

$$d_3 = \frac{(c + 4dE_c + 10eE_c^2 + \ldots)\,E_m^2 + (\frac{5}{4}e + \ldots)\,E_m^4 + \ldots}{2(2a + 4bE_c + 6cE_c^2 + \frac{3}{2}cE_m^2 + \ldots)} \times 100 \qquad (8)$$

where E_c is the d-c grid bias, E_m is the peak a-c signal voltage, and a, b, c, etc. are tube constants. A minimum of the third harmonic will occur when the numerator of the equation is equal to zero. When the signal amplitude is small (less than about 0.1 volt) the conditions for a minimum are fairly independent of signal amplitude and are satisfied approximately when $c + 4dE_c + 10eE_c^2 = 0$. The constants are dependent upon tube characteristics and operating voltages and, except for a, may be either positive or negative. The magnitude of a is normally much greater than that of b, which in turn is usually greater than c, etc.

The relation between percent distortion and grid bias in the region of a minimum is a function of the various circuit constants. A typical curve, drawn for an assumed set of constants, is shown in Fig. 4 and was determined from the equation

$$d_3 = \frac{(c + 4dE_c + 10eE_c^2)E_m^2}{4a + 8bE_c + 12cE_c^2} \times 100 \qquad (9)$$

As can be seen from Fig. 4, the relation between distortion and grid bias is fairly linear in the immediate vicinity of the minimum, so that the percent third harmonic is proportional to the deviation of grid bias from the minimum. In the example of Fig. 4, the increase in third harmonic distortion is approximately 0.00004 percent per volt deviation from the minimum. Similar characteristics will be obtained with variation in plate voltage, filament voltage, or other circuit parameters.

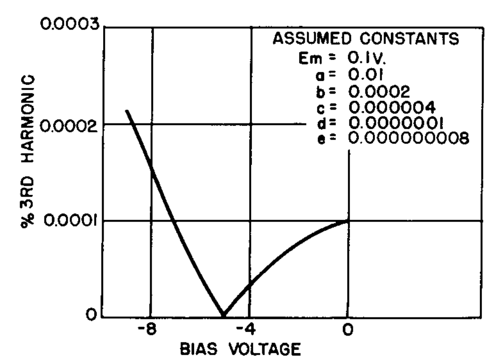

Fig. 4 - Percent third harmonic as a function of grid bias for assumed tube constants

When an amplifier is adjusted for a minimum of one harmonic of a given signal, the conditions for a minimum will no longer be exactly fulfilled if another signal is introduced; that is, the presence of a second signal affects the conditions for a minimum of a given harmonic of the first signal. The same is true regarding conditions for a minimum of an intermodulation term. A comparison of conditions for minimum second- and third-order distortions in a single amplifier is given in Table 1. For two unequal inputs, the minimums will occur for the two signals under different conditions.

TABLE 1
Conditions for Minimum Distortion

Distortion	Single Input, Harmonic	Two Equal Inputs	
		Harmonic	Intermodulation
2nd order	$b + dE_m^2 = 0$	$b + 4dE_m^2 = 0$	$b + 3dE_m^2 = 0$
3rd order	$c + (5/4)eE_m^2 = 0$	$c + (25/4)eE_m^2 = 0$	$c + (25/6)eE_m^2 = 0$

DISTORTION IN EXPERIMENTAL PUSH-PULL MULTICOUPLER

Even-Order Terms

A two-unit multicoupler, consisting of push-pull input amplifiers driving push-pull output cathode followers, was designed for use in measuring distortion in push-pull circuits. Circuit description and measuring procedures are given in the appendix. This design was not intended for producing unusually low values of distortion but rather to permit a study of the improvements obtainable with harmonic cancellation and minimums in a push-pull circuit.

While it is impossible to obtain identical tubes, it is possible to adjust operating voltages or other circuit parameters so that the characteristics of both tubes in a push-pull amplifier are very similar over a limited region of grid swing, causing at least one even-order distortion term to cancel almost completely if its amplitude is within a certain range. The effect on second-harmonic cancellation due to variation of the grid bias of one input amplifier is shown in Fig. 5 and the result of varying the bias of one of the output cathode followers is shown in Fig. 6. These figures indicate the degree of reduction obtainable for the second harmonic by proper circuit adjustment. The input signal for these measurements was 1.0 volt (0.5 volt each side of ground).

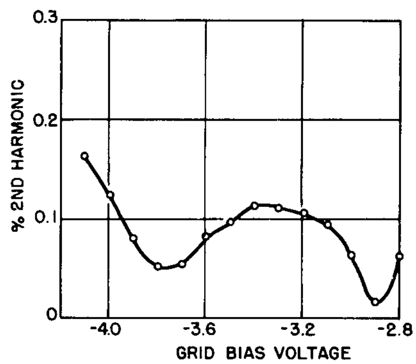

Fig. 5 - Percent second harmonic as a function of grid bias of the input amplifier

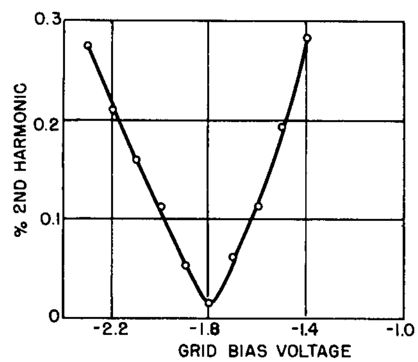

Fig. 6 - Percent second harmonic as a function of the grid bias of the output cathode follower

Figure 7 shows the variation in percent second harmonic with respect to input signal amplitude with the multicoupler adjusted for the best cancellation of the second harmonic that could be obtained for an input signal of 0.6 volt or 1.0 volt. The dashed line indicates the shape of the curve that might be obtained for this harmonic with a random selection of operating conditions. This figure shows that harmonic cancellation is dependent upon the amplitude of the input signal.

Operating conditions for minimum values of second-harmonic distortion are not necessarily the same as the conditions for minimum values of other even-order distortion terms. However, it was found that much better results in lowering over-all even harmonic distortion were obtained by adjusting for cancellation of the second harmonic than for the fourth.

Second-order distortion in push-pull circuits is generally on the order of 20 to 30 db below that in a single-ended circuit, the amount of reduction being dependent upon the degree of balance present in the individual circuit. An additional 20 to 30 db reduction is possible with careful adjustment for cancellation, but only for a limited range of signal amplitude. The reduction in even-order distortion obtained in push-pull circuits even without special adjustment is significant.

Odd-Order Terms

With proper adjustment of the circuit parameters it is often possible to obtain a minimum of an odd-order harmonic or intermodulation term. It was found that several methods or combinations of methods are possible for odd-order distortion reduction. For example, the tubes in a push-pull amplifier may be operated on opposite sides of a minimum for a particular odd-order distortion term. The distortion voltages in the output will then be in phase and can be adjusted to equal amplitude. Amplifiers having two or more stages, such as the multicoupler described in this report, can be so adjusted that a given odd-order distortion term produced by the first amplifier can be at least partly cancelled in the second amplifier if the grid-cathode voltages of the two tubes are approximately equal. As in the case of even-order cancellation, these minimums will be critical with respect to operating voltages, input signal amplitude, and other circuit parameters.

When the experimental multicoupler was adjusted for cancellation of the third harmonic with 0.6 or 1.0 volt input, the percent third-harmonic distortion for signals of any other amplitude (except for very small signals – less than 0.1 volt) was greater than the percent distortion at this minimum, as shown in Fig. 8. Considerably lower distortion was obtained with the minimum at 0.6 volt than with the minimum at 1.0 volt. When the signal became greater than that for which the cancellation was adjusted, the percent harmonic increased sharply and was soon of the same order of magnitude that it has under more general conditions, indicated by the dashed line in Fig. 8.

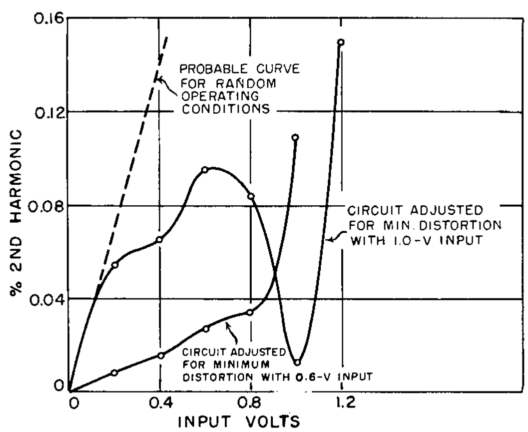

Fig. 7 - Percent second harmonic as a function of the multicoupler input-signal amplitude with the circuit adjusted for second-harmonic cancellation

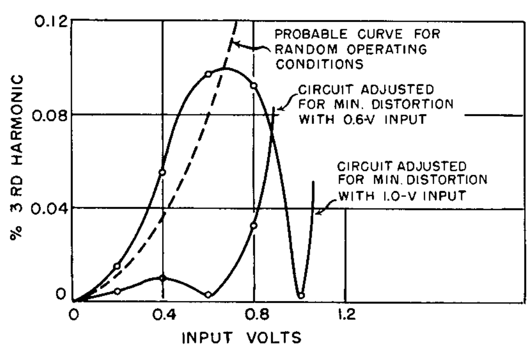

Fig. 8 - Percent third harmonic as a function of the multicoupler input-signal amplitude with the circuit adjusted for third-harmonic cancellation

With the test multicoupler adjusted for third-harmonic cancellation with 1.0 volt input, it was found that the percent harmonic of this signal increased in the presence of an interfering signal greater than 0.1 volt rms. This effect is independent of the frequency of the interfering signal and is a result of a change in operating conditions.

The effect on third-harmonic distortion of varying the plate supply voltage to the test multicoupler is shown in Fig. 9. Similar results were obtained for the second harmonic. Figures 10 and 11 show the change in percent third-harmonic distortion when the bias voltage of an input amplifier and a cathode follower was varied. These curves are comparable to those obtained for the second harmonic (Figs. 5 and 6) except that the bias adjustment of the cathode follower was more critical for the second harmonic than for the third.

Measured values of intermodulation distortion were approximately equal to those predicted from the percent harmonic distortion (2). Since conditions for harmonic cancellation do not, in general, coincide with those for combination frequencies of the same order, the approximate theoretical relationships between the amplitudes of harmonic and intermodulation terms (2) will not hold true in the vicinity of the cancellation.

Variation with Time

The characteristics of vacuum tubes are known to vary with time (3), so that if an amplifier is adjusted for harmonic cancellation it cannot be expected to maintain this condition indefinitely. Hence it was decided to measure the variation of the percent third harmonic in the experimental multicoupler over a period of 100 hours after it had been adjusted for a third-harmonic minimum with an input of 1.0 volt. All circuit parameters were maintained as nearly constant as possible with varying line voltages. The results of this test (Fig. 12) show that the over-all change in third-harmonic distortion over a 100-hour period was on the order of 30 db, from 0.0036 percent at the beginning of the test to about 0.1 percent at the end.

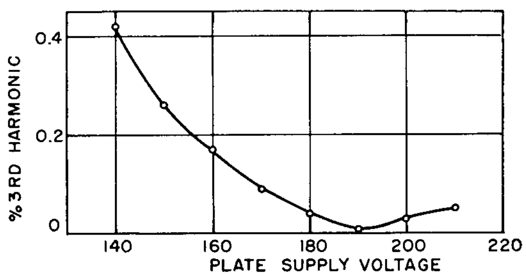

Fig. 9 - Percent third harmonic as a function of the multicoupler plate-supply voltage

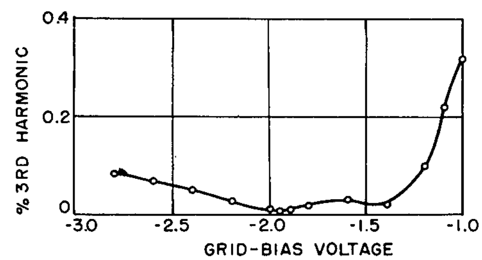

Fig. 10 - Percent third harmonic as a function of the grid bias of the input amplifier

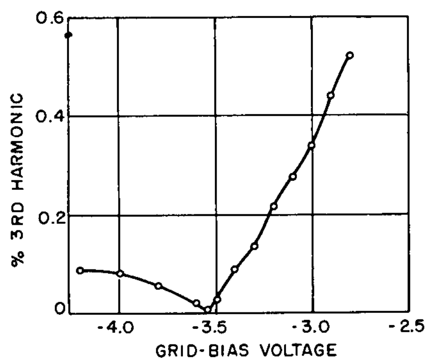

Fig. 11 - Percent third harmonic as a function of the grid bias of the output cathode follower

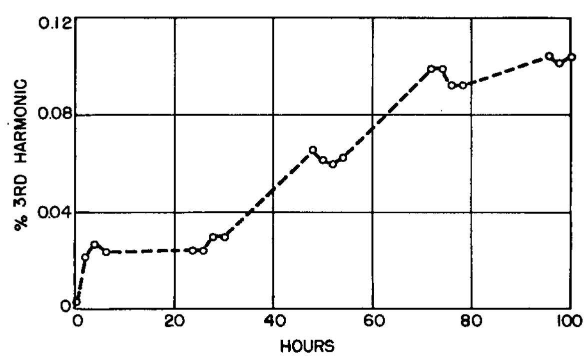

Fig. 12 - Variation of the percent third harmonic of multicoupler with time in the 100-hour stability test

Effect of Feedback

Additional feedback was incorporated in the input amplifiers of the multicoupler by simultaneously varying the portion of their cathode resistors bypassed to ground, so that these amplifiers became cathode-degenerate amplifiers. The multicoupler gain was thereby reduced from three to approximately unity, while percent second- and third-harmonic distortion on each side of the circuit decreased by about 20 db under most operating conditions.

In a few cases it was noticed that the harmonic distortion tended to rise at first as feedback was introduced. Evidently the circuit had been operating in the vicinity of a harmonic minimum or cancellation when no feedback was present, showing that distortion will not always be reduced by feedback.

CONCLUSIONS

For no interference to reception, the distortion from a receiver multicoupler should be below the noise level of the receivers used in conjunction with it. Because of the impossibility of obtaining perfectly linear tubes, other means must be employed in conjunction with practical tubes in an attempt to obtain the desired freedom from distortion.

1. Push-pull operation is an effective means of reducing even-order distortion some 20 to 30 db below that obtained from single-ended amplifiers, but it is not by itself capable of attaining the freedom from distortion desired in multicoupler circuits.

2. If the transconductance of one tube in a push-pull amplifier is different from that of the other tube, the ratio of the even-order distortion produced by this circuit to that produced by a single tube is approximately $\Delta g_m/g_m$.

3. If $\partial g_m/\partial E_c$ is different for the two tubes, the ratio of second harmonic produced in a push-pull circuit to that produced by a single tube is approximately $[\Delta(\partial g_m)/(\partial E_c)]/[(\partial g_m)/(\partial E_c)]$.

4. If the distortion voltages in a push-pull circuit are unequal or of different phase, the net distortion is given by $E_d = \sqrt{E_1^2 + E_2^2 - 2E_1E_2\cos\theta_d}$.

5. A given odd-order distortion term produced in one stage of an amplifier can be reduced on the order of 20 db by the distortion in a succeeding stage if the distortion voltages are out of phase and the grid-cathode voltages of the two tubes are approximately equal. However, the improvement in distortion thus obtained is dependent upon signal amplitude and other circuit parameters.

6. Although given odd-order distortion terms can be reduced by operating the two tubes in a push-pull circuit on opposite sides of a minimum so that distortion voltages cancel in the output, the resulting unbalance will usually have a degrading effect on even-order cancellation.

7. The criticalness of adjustments for distortion cancellation with respect to operating voltages and their variation with time may make their use undesirable. However, operation in the vicinity of a minimum or cancellation, without critical adjustments, will result in lower distortion than that obtained by random selection of operating conditions.

8. Feedback is an effective means of reducing distortion in vacuum-tube amplifiers since, in general, it reduces the magnitude of all distortion terms. Distortion reduction up to 20 db or so can often be obtained by changing conventional amplifiers to cathode followers or cathode degenerate amplifiers, although a decrease in gain will also result.

9. The simultaneous use of several of these methods of distortion reduction will usually, but not always, result in lower distortion than that obtained by the use of only one method.

* * *

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APPENDIX
Experimental Multicoupler and Measuring System

The two-stage multicoupler on which the measurements in this report were made is shown schematically in Fig. A1. This circuit was designed for use in testing at audio frequencies only, and hence should not be considered a practical multicoupler circuit. The use of audio frequencies in these measurements made possible the determination of the circuit characteristics without becoming involved in high-frequency amplifier design. This made it possible to neglect such effects as stray capacitance and lead inductance, permitting placement of adjustable circuit components in a convenient position.

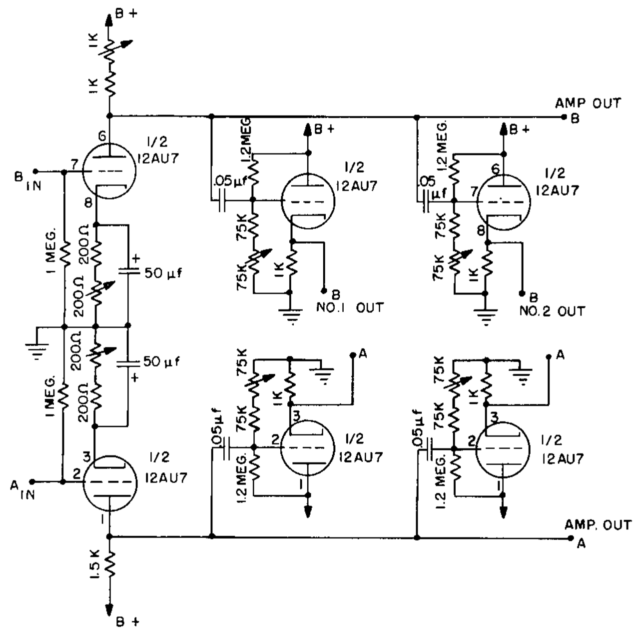

Fig. A1 - Circuit diagram of experimental push-pull multicoupler

The multicoupler consists of three dual triodes, one of which is the input amplifier. This amplifier drives two pairs of cathode followers, furnishing two push-pull outputs. Adjustment for harmonic minimums or cancellation can be made by independently varying the load resistor for one of the input amplifiers. The signal amplification provided by the first stage is about three.

Measurement of harmonic distortion in the push-pull multicoupler was made by the equivalent-signal method using the circuit shown in Fig. A2. The 3-kc fundamental signal was produced by audio oscillator No. 1, with its harmonics attenuated by means of a filter. The fundamental input voltage to the multicoupler was measured at its input terminals.

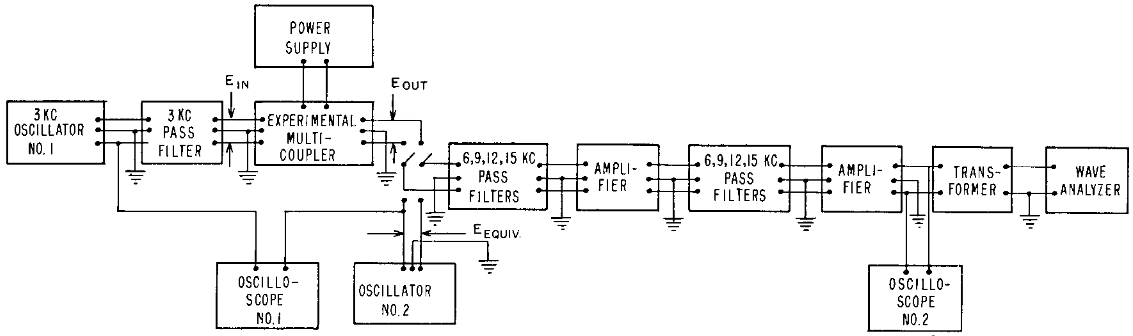

Fig. A2 - Block diagram of distortion-measuring system used with experimental push-pull multicoupler

The filters, amplifiers, and wave analyzer connected to the multicoupler output constitute a voltmeter tuned to a harmonic of 3 kc. All amplifiers in the measuring circuit were single-ended. Filters on the two sides of the push-pull circuit were electrically independent and were of the form shown in Fig. A3. Each filter attenuated all but the desired harmonic by at least 40 db. The amplitude and phase of one filter were adjusted for balance before each measurement in order to minimize any errors which might be contributed by unbalance in the measuring circuit. Unbalance was indicated by the meter shown in Fig. A4. The General Radio type 736-A Wave Analyzer was tuned for maximum reading, which was recorded.

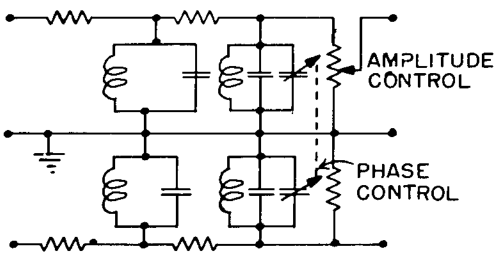

Fig. A3 - Typical filter used in measuring circuit

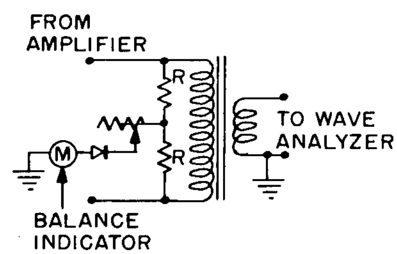

Fig. A4 - Transformer and balance indicator

Audio oscillator No. 2 was then connected to the measuring circuit and adjusted to the desired harmonic of 3 kc by means of oscilloscope No. 1. Its output was adjusted so that the reading previously noted on the wave analyzer was duplicated. The distortion was expressed as the ratio of the output voltage of oscillator No. 2 to the fundamental output from the multicoupler.

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