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BALANCED FEED-BACK AMPLIFIERS*

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Summary—*The following paper describes and analyzes mathematically a new principle in amplifier design. It is shown how noise, phase shift, frequency distortion, etc., can be largely eliminated by use of the "balanced feed-back principle" without reduction of the over-all gain of the amplifier.*

By means of balanced feedback the linear range of an amplifier using ordinary receiving-type tubes has been extended from an upper limit of 600,000 up to 2,500,000 cycles. Theoretical and experimental results were found to check closely.

INTRODUCTION

IN RECENT years an important change in amplifier design was introduced by the development of the stabilized feedback or the negative feed-back principle.[1] This design represented a substantial improvement in the performance of amplifiers; by means of this principle the amplifier response can be made linear and practically independent of line-voltage fluctuations, and noise and distortions are reduced. These improvements are made possible by the return of a fraction of the output to the input to be used as a controlling voltage. Since the energy fed back is in opposite direction to the input signal, the feedback reduces the signal output, and in the cases where performance requirements are very strict, the reduction of the over-all gain may be so large that it becomes impractical to use such a system. It is desired, then, to develop an amplifier which will possess the advantages of the negative feedback without its disadvantage—the reduction of the over-all amplification. Such a design is possible by means of application of the balanced feed-back principle.

BALANCED FEED-BACK AMPLIFIERS

1. *The Balanced Feed-Back Principle*

The name balanced feedback is derived from the fact that two controlling voltages, balanced against each other, are used at the input of the amplifier for the purpose of controlling its performance. One of

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[1] H. S. Black, "Stabilized feedback amplifiers," *Bell Sys. Tech. Jour.*, vol. 13, p. 1; January, (1934).

these voltages is obtained from the output of the amplifier and is the conventional negative feedback which regulates the performance of the amplifier, and will be referred to in this paper as the *negative feed-back voltage*. The other feed-back voltage, in opposite polarity to the negative feedback, and hence called the *positive feed-back voltage*, is obtained in such a way that it is always proportional to the input signal and is independent of frequency over the range of frequencies it is desired to amplify linearly. The positive and negative feedbacks are made normally equal to each other, and therefore, when the performance of the amplifier is normal, they cancel each other and, hence, have no effect on the output. But if the output should for some reason differ

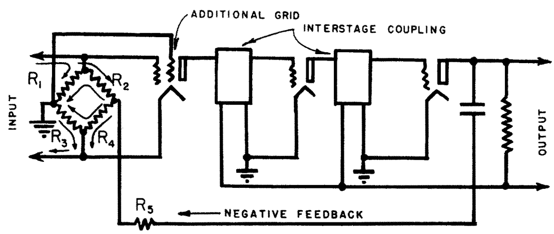


Fig. 1—An idealized balanced feed-back amplifier. An additional grid is used for the control of the performance.

from proportionality to the input, the feed-back circuits introduce voltages at the input of the amplifier in such a direction and of such a magnitude that the output is changed back to normal. In its operation, the balanced feed-back principle is very similar to the ordinary mechanical governor in steam engines, turbines, etc., in that the governor is acting only when the output differs from the desired normal operating conditions.

The principle of the balanced feedback is shown in the idealized circuit, Fig. 1. Except for the two feed-back circuits and additional control grid in the first tube, the amplifier is of the conventional design using whatever interstage coupling may be required for the specific application. Across the resistances of the bridge in the input circuit there are two voltages, one being the signal input, and the other being a fraction of the output returned to the input. Across the resistance R_3 the two voltages are in the opposite direction, as shown by current arrows in Fig. 1, and therefore, by proper choice of various resistances, the voltage across resistance R_3 can be made zero. As is seen in Fig. 1, resistance R_3 is connected between the cathode and the additional grid of the first tube; if the output is proportional to the input, the voltage across R_3 is zero and the additional grid has no effect on the plate current of the first tube. But if the output deviates from proportionality, a voltage will be introduced across R_3 and the additional grid in the first tube will be at some potential with respect to its cathode. The output of the amplifier will be changed, accordingly, so as to tend to eliminate the original deviation and restore perfect proportionality.

2. Polarity of the Two Feedbacks

The feed-back voltages impressed at the input of the amplifier must satisfy two conditions. (1) The two feedbacks must be in opposite polarity. Since each tube and each interstage transformer, if they are used, produce a reversal of polarity, care must be taken to have the negative feed-back voltage actually of opposite polarity to the positive feedback. (2) The additional grid must be in proper polarity with respect to the control grid of the first tube. For example, if the amplifier output should become too low for some reason, then the voltage produced on the additional grid must be of the same polarity as the voltage of the control grid to increase the output to the proper level. Accordingly, the negative feedback must be of opposite polarity to the input and the positive feedback must be of the same polarity as the input.

These two conditions are obviously essential. Actual polarity of the two feedbacks depends upon the specific circuit used in the main amplifier and upon the manner in which the positive feedback is obtained.

3. Performance Equations for Balanced Feedback

The effect of balanced feedback as compared to the negative feedback is shown by the following derivation:

Let,

e = signal input voltage

A = amplification constant for the entire amplifier

Ae = signal output voltage without feedback

n = noise output voltage without feedback

$d(E)$ = distortion output voltage without feedback

β = propagation constant of the negative feed-back circuit, i.e., the fraction of the output returned to the input

α = propagation constant of the positive feed-back circuit, i.e., a number times the input voltage. May be greater or less than 1.

E = signal output voltage with balanced feedback

N = noise output voltage with balanced feedback

D = distortion output voltage with balanced feedback.

The above notation is perfectly general and applies to an amplifier which utilizes both positive and negative feedback. All of the above symbols, except α and β, are obvious and have the usual meanings for all amplifiers. Definition of factor α, however, depends upon the particular amplifier and the way that positive feedback is introduced into the input. In general, α is defined by the ratio of the voltage developed by the positive feed-back circuit to the signal input voltage at the input grid of the first stage. Definition of β is perfectly general as defined above. For instance, in Fig. 1, assuming that R_1, R_2, R_3, and R_4 are equal, $\beta = R_3/[2(R_3+R_5)]$. Assuming that the two control grids in Fig. 1 have the same amplification factor, then $\alpha = R_3/[R_3+R_1] = \frac{1}{2}$.

The output voltage without feedback is $Ae+n+d(E)$. The balanced feed-back voltage is composed of positive feed-back voltage αe, and negative feed-back voltage $\beta(E+N+D)$. The total feed-back voltage is (at the input of the amplifier)

$$\alpha e + \beta(E + N + D). \tag{1}$$

The output voltage with balanced feedback is composed of the output voltage without balanced feedback plus the output due to the balanced feedback at the input. Hence, the output with the balanced feedback is

$$E + N + D = Ae + n + d(E) + \alpha Ae + \beta A(E + N + D) \tag{2}$$

$$(E + N + D)(1 - \beta A) = Ae(1 + \alpha) + n + d(E) \tag{3}$$

$$E + N + D = \frac{Ae(1 + \alpha)}{1 - \beta A} + \frac{n}{1 - \beta A} + \frac{d(E)}{1 - \beta A} \cdot \tag{4}$$

If the amplifier is so adjusted that the positive feedback is equal and opposite to the negative feedback, i.e., $\alpha = -\beta A$, the performance equation for the balanced feed-back amplifier becomes

$$E + N + D = Ae + \frac{n}{1 - \beta A} + \frac{d(E)}{1 - \beta A} \cdot \tag{5}$$

Equation (5) shows that distortion, noise, etc., are reduced by the factor $1/(1-\beta A)$, while the over-all gain of the amplifier is not affected by the introduction of the balanced feedback. Note that if the positive feedback is zero, $\alpha = 0$, and (4) becomes the performance equation for the conventional negative feed-back amplifiers.[1]

$$E + N + D = \frac{Ae}{1 - \beta A} + \frac{n}{1 - \beta A} + \frac{d(E)}{1 - \beta A} \cdot \tag{6}$$

Equations (5) and (6) show the main difference between the balanced feedback and the negative feedback. In the negative feedback, equation (6), the gain, noise, and distortion are all reduced by the same factor. In the balanced feed-back amplifiers there is a definite discrimination against noise and distortion, while the gain is not affected.

It must be remembered, however, that the only essential difference between (5) and (6) is the reduction of gain in the latter case. The same result can be achieved by means of negative feedback alone, if the amplifier possesses excessive gain, or if it is possible to increase sufficiently the mutual conductance of one or more tubes, or by addition of another stage. *If this is possible* the results obtained by means of negative feedback alone will be identical with those obtained by means of balanced feedback, with the additional advantage that the negative feed-back circuits tend to be simpler than those employed with balanced feedback. But as mentioned in the Introduction, there are cases where the particular requirements do not allow the reduction of the over-all gain of the amplifier.

From these equations the performance of the amplifier with balanced feedback may be determined. Frequency response, stability, delay distortion, critical points, etc., may be determined by proper manipulation.

4. Frequency Response of Balanced Feed-Back Amplifiers

The amplification constant of an amplifier is a complex quantity and is a function of frequency. The problem of calculation of the response of the amplifier can be subdivided for convenience into the calculation of the absolute value and the calculation of the corresponding

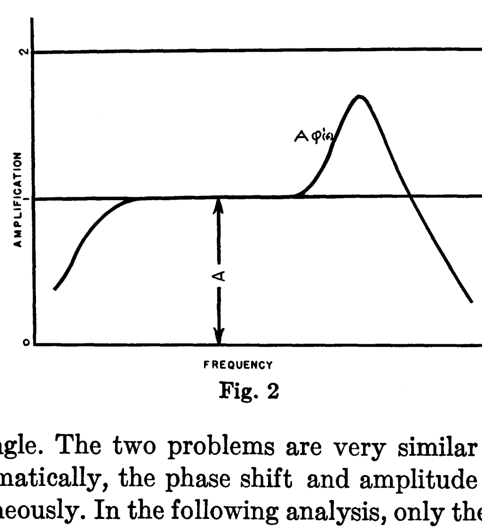


Fig. 2

phase-shift angle. The two problems are very similar and, as can be shown mathematically, the phase shift and amplitude distortion take place simultaneously. In the following analysis, only the absolute value of the response will be considered, with the understanding that the balanced feedback affects the phase shift in a similar manner and can be easily determined.

Referring to Fig. 2, let $\phi(f)$ be the factor by which the amplification of the balanced feed-back amplifier changes with frequency, $\phi'(f)$ be the factor by which the amplification constant A changes with frequency, and $\phi''(f)$ be the factor by which the positive feedback α changes with frequency. Assuming zero noise or other distortion, (4) becomes

$$E = A\phi'(f)e \frac{1 + \alpha\phi''(f)}{1 - \beta A\phi'(f)} \tag{7}$$

$$= Ae\phi(f) \tag{8}$$

where,

$$\phi(f) = \phi'(f) \frac{1 + \alpha\phi''(f)}{1 - \beta A\phi'(f)} \cdot \tag{9}$$

If $\alpha\phi''(f) \gg 1$ and $\beta A\phi'(f) \gg 1$, and $\alpha = -\beta A$. Then,

$$\phi(f) = \phi''(f). \tag{10}$$

This means that if the positive and the negative feed-back voltages are made normally equal and very much larger than one, the output will

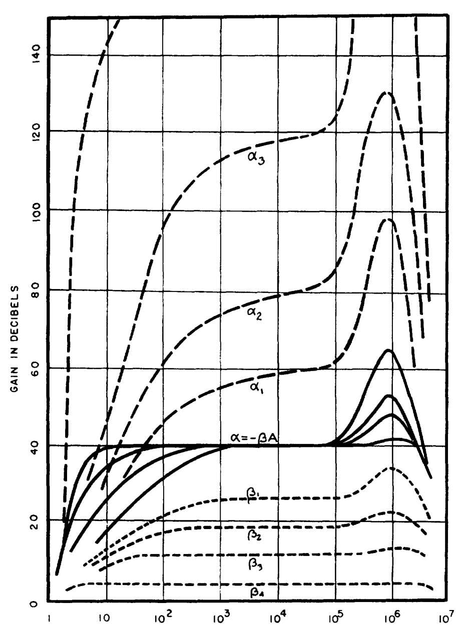


Fig. 3—Theoretical curves showing the effect of balanced feedback.

be a function of the performance of the positive feed-back voltage which can be made independent of frequency over the range of frequencies that it is desired to amplify without distortion, as is discussed later. If this condition is fulfilled, the performance of the entire amplifier will be independent of frequency over approximately the same range as the distortionless range of the positive feed-back circuit.

Fig. 3 shows the theoretical frequency-response curves obtained from (7) and a known typical curve for a two-stage resistance-capacitance-coupled amplifier. The dotted curves show the effect of the negative feedback alone; these show that the negative feedback makes the response of the amplifier linear over a large range of frequencies, but at the same time decreases the gain. The dashed curves show the effect of positive feedback alone. These are essentially the same as the response without any feedback, the difference being in the larger gain and the sharper cutoff outside the desired range. Balanced negative and positive voltages applied at the same time give a family of curves which approaches a straight line more and more as the ratio of the feedback to the input is made larger.

Practical Balanced Feed-Back Amplifiers

1. Methods of Obtaining Positive Feedback

The above discussion and Fig. 3 show that it is desirable to have as high a value of balanced feedback as possible. There is no difficulty in obtaining a high value of negative feedback; the positive feedback is limited, however, by the type of circuit employed and tubes used. If a circuit similar to the one shown in Fig. 1 is used, and it is assumed that the additional grid has the same degree of control as the control grid, then the maximum value of positive feedback is one. This value is ordinarily too low, and either a more sensitive additional grid must be used or the positive feedback must be obtained in another way. At the present time there are no tubes on the market with two extremely sensitive grids, and therefore other methods must be devised to obtain the sufficiently high value of positive feedback.

Figs. 4 and 5 show possible methods of obtaining a high value of positive feedback. In Fig. 4, the second tube amplifies the output from the screen-grid circuit of the first stage. The output of the second tube is returned to the input of the amplifier as positive feedback, since the output of the second tube is in phase with the input of the amplifier. By proper adjustment of the circuit, the effective positive feedback can be made very large, as can be seen from (6) and from

$$E' = \frac{A'e'}{1 - \gamma A'} \tag{11}$$

where A' is now the amplification of the positive feed-back circuit and

γ is its feed-back ratio. If $\gamma A'$ is made almost equal to 1, then the output becomes very large, thus making the effective input to the amplifier much higher. Fig. 5 shows a similar circuit, except that the positive feed-back circuit is also a part of the main amplifier.

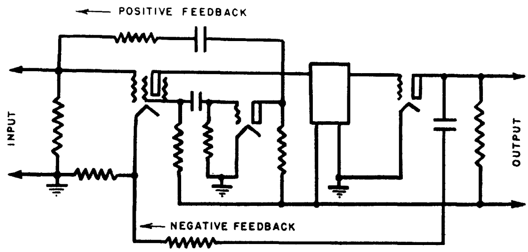


Fig. 4

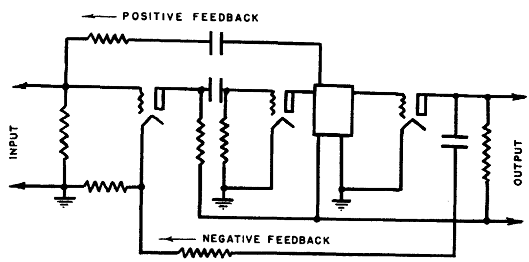


Fig. 5

In either of these two cases, the part of the amplifier that is involved in the positive feed-back circuit must be designed to give a linear response over the entire range of frequencies it is desired to amplify linearly. Since the gain of this part of the circuit does not have to be large, this requirement is usually not very difficult to fulfill in practice.

In all of the circuits considered, i.e., Figs. 1, 4, and 5, there are three voltages present at the input of the amplifier. One of these is the signal input voltage, the second is the conventional negative feed-back voltage obtained from the output of the amplifier, and the third is a voltage proportional to the signal input voltage and is used to balance out the negative feed-back voltage when the operation of the amplifier is perfect. This last voltage, termed above as the positive feed-back voltage, may be obtained in several ways mentioned above and shown in Figs. 1, 4, and 5. Its magnitude is always defined by its propagation constant α

$$\alpha = \frac{\text{positive feed-back voltage at input}}{\text{signal input voltage}} \cdot \tag{12}$$

The propagation constant of the negative feed-back circuit is defined as β and is always equal to

$$\beta = \frac{\text{negative feed-back voltage at input}}{\text{signal output voltage}} \cdot \tag{13}$$

The positive feed-back voltage is determined by the type of the circuit used. For instance, in Fig. 1, the positive feed-back voltage is simply a fraction of the input voltage, depending upon the setting of the bridge. In circuits such as are shown in Figs. 4 and 5, the positive feedback is obtained by means of a regenerative network, the exact value of positive feed-back voltage being determined by means of (11).

If in the future a tube with a very sensitive additional grid, not necessarily linear, is developed, the circuit shown in Fig. 1 will become practical and ideal, since no additional parts are required to produce positive feedback.

2. Construction of Balanced Feed-Back Amplifiers

In actual construction of the amplifier used care was taken to minimize all stray capacitances between the feed-back leads and ground, as well as the stray capacitances between the various stages. By arranging the tubes horizontally in series, with shields in between, it was possible to make the stray capacitance of each stage small. By placing the tubes in a zigzag arrangement between two shields so that the input and the output of the amplifier are very close together, the feed-back leads are made very short and the feed-back circuits become practically independent of frequency.

Design of a Balanced Feed-Back Amplifier

The general scheme of applying the balanced feed-back principle to an amplifier of any type is as follows:

(1) Design of the high-gain amplifier so that the amplitude of the output is sufficiently high over the entire range of frequencies it is desired to amplify linearly. It is necessary to design it so that the amplification does not drop very far *below* the desired normal; it is unimportant how high it may become over certain ranges of frequencies. The design of the amplifier is conventional, the type of interstage coupling depending upon the specific requirements. In resistance-capacitance-coupled amplifiers the response curve, however, should be kept from dropping too low by means of small inductances placed in the plate leads of each tube, as suggested by Kell.[2] The value of the inductance

[2] R. D. Kell, "Description of experimental television transmitting apparatus," Proc. I.R.E., vol. 21, pp. 1674–1691; December, (1933).

depends upon the stray capacitance of each stage and the highest frequency desired to amplify.

(2) The two feed-back circuits must be designed so that they are absolutely linear over the entire working range of frequencies. If both of the feed-back circuits are properly designed, the negative feedback will reduce the distortion and make the amplifier linear; the positive feedback will restore the gain to the former level, thus giving a high over-all gain without appreciable distortion of any kind.

(3) The stability of the amplifier depends upon the performance of the positive and negative feed-back circuits. Providing the positive feed-back circuit is properly designed, that is, the regeneration is not allowed to become too great, it cannot cause any instability. If the main amplifier uses negative feedback across more than two stages, or in cases where transformer coupling is used, phase reversals may produce oscillations or "singing." However, H. S. Black[1] has shown that negative feedback can be applied over as many as five stages without producing instability. Since the design of the negative feed-back circuits in a balanced feed-back amplifier in no way differs from the conventional negative feed-back amplifiers, the practical and theoretical limitations of balanced feed-back amplifiers are essentially the same as those of negative feed-back amplifiers. A simplified discussion of the question of stability, its dependence upon the phase shift of the amplifier, and the effect of feedback on phase distortion, will be found very well discussed in Black's article.[1] A rigorous treatment of the question of stability is given by H. Nyquist,[3] and E. Peterson, J. G. Kreer, and L. A. Ware.[4]

The main factors to consider in design of the feed-back circuits are:

(a) The type of stabilization required, either current or voltage. If the negative feedback is proportional to the current output, the balanced feedback will tend to keep the current output constant, whereas, if the negative feedback is proportional to the output voltage, the latter will be stabilized.

(b) Polarity. As previously stated, the negative feedback must be of opposite polarity to the input and the positive feedback must be of the same polarity as the input.

Experimental Results

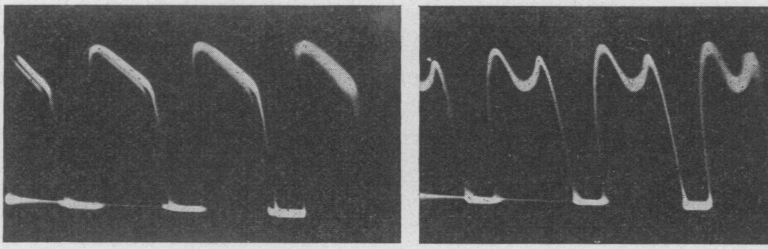
1. *Restoration of Wave Shape*

Figs. 6 and 7 show the effect of balanced feedback on the performance of an amplifier, with the tubes very badly overloaded, thus pro-

[3] H. Nyquist, "Regeneration theory," *Bell Sys. Tech. Jour.*, vol. 11, p. 126; July, (1932).

[4] E. Peterson, J. G. Kreer, L. A. Ware, "Regeneration theory and experiment," Proc. I.R.E., vol. 22, pp. 1191–1210; October, (1934).

ducing distortion. Fig. 6(a) is an oscillogram showing the output without any feedback. Fig. 6(b) shows the effect of a small value of balanced



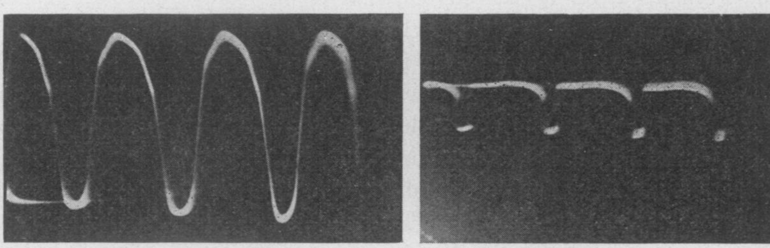
(a) (b)

Fig. 6

(a) An oscillogram showing the output of an amplifier with sine-wave input. Direct-current bias = -3 volts. Signal voltage is 10 volts.

(b) An oscillogram showing the output of an amplifier under conditions of Fig. 6(a), but with a small value of balanced feedback.

feedback, and Fig. 7(a) shows the effect of a fairly large value of feedback. Although the wave shape is not completely restored to that of the sine-wave input, it is much improved. Figs. 6(a), 6(b), and 7(a) were taken under the same operating conditions, and show that the elimination of distortion took place without any reduction of the over-all gain. Fig. 7(b) is an oscillogram showing the feed-back voltage corresponding



(a) (b)

Fig. 7

(a) An oscillogram showing the output under the same conditions as Fig. 6, but with a large value of balanced feedback. While not a sine-wave, it resembles the sine-wave input much more than Fig. 6(a).

(b) An oscillogram showing the voltage across the feed-back bridge with the output as shown in Fig. 7(a).

to the feed-back conditions of Fig. 7(a); this is the voltage that must be amplified, subjected to distortion, and combined with the distorted output of Fig. 6(a) to produce the improved wave shape shown in Fig. 7(a). (The lopsidedness of the oscillograms, giving three values of voltage for one time in several places, is not due to the distortion in amplifier, but due to a faulty sweep of the cathode-ray oscillograph used to obtain these oscillograms.)

2. Frequency Characteristics of a Balanced Feed-Back Amplifier

Application of the balanced feed-back principle to a resistance-capacitance-coupled amplifier (two stages (Fig. 4)) improved its frequency-response characteristic as shown in Fig. 8. Curve *A* in Fig. 8 shows the response of the amplifier without any feedback and without

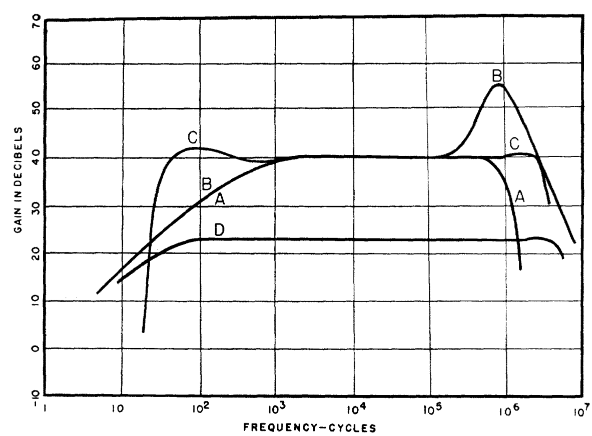


Fig. 8—Frequency response of an amplifier under various conditions. Curve *C* represents the response with balanced feedback, curve *D* with negative feedback

inductances in the plate leads. Curve *B* shows the response without feedback, but with inductances in the plate leads, which cause the large hump at the higher frequencies. The inductances are used, as described above, to prevent a too low cutoff frequency. Curve *C* shows the response with balanced feedback; the hump is practically entirely removed, and the regions of amplification that are not too low are restored to normal amplification. The same linear range can be obtained by means of negative feedback alone as shown by curve *D*, but only at reduced gain.

3. Degree of Predictability from Theoretical Considerations

Using the value of stray capacitance per stage, which depends upon the quality of construction, and the desired cutoff frequency, it is possible to calculate the performance of the amplifier. The response curve for the amplifier without feedback (this depends upon the type of coupling between stages, tubes used, stray capacitance, etc.) may be either calculated or obtained experimentally. The response curve for the amplifier with the balanced feedback may then be calculated from the theoretical considerations developed above, and by making use of

(7). The accuracy with which these curves may be predetermined can be seen in Fig. 9. The theoretical curve, within the experimental errors in measurements, is the same as measured in the laboratory.

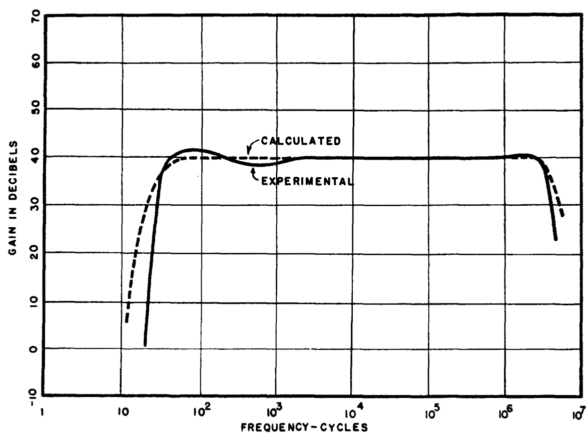


Fig. 9—Degree of predictability.

Conclusions

The experimental results verify the theoretical expectations and show that balanced feedback can be applied to various amplifiers, for various purposes, without undue elaborations. The theory agrees very closely with actual results, and therefore the design procedure is simple.

Balanced feed-back principle can readily be applied to wide-range television amplifiers. An amplifier using ordinary receiving-type tubes, i.e., RCA-57, has been built and its linear output was extended from a range of 1000 to 600,000 cycles to a range of essentially linear response from 30 to 2,500,000 cycles. By means of smaller tubes, such as RCA-954, it is to be expected that linear response up to 5,000,000 cycles can be obtained at a high gain.

Application of balanced feedback to audio-frequency amplifiers in radio sets may be of value. It would tend to eliminate noises that are developed in the last stage due to aging of the tube, gases, etc., and thus prolong the usable life of the tube.