

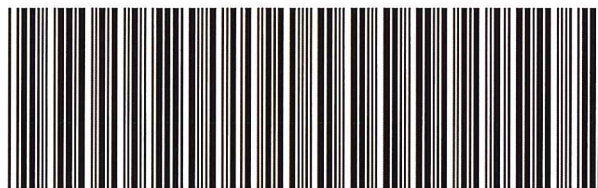
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The Bell System Technical Journal

January, 1934

Stabilized Feedback Amplifiers*

By H. S. BLACK

This paper describes and explains the theory of the feedback principle and then demonstrates how stability of amplification and reduction of modulation products, as well as certain other advantages, follow when stabilized feedback is applied to an amplifier. The underlying principle of design by means of which singing is avoided is next set forth. The paper concludes with some examples of results obtained on amplifiers which have been built employing this new principle.

The carrier-in-cable system dealt with in a companion paper¹ involves many amplifiers in tandem with many telephone channels passing through each amplifier and constitutes, therefore, an ideal field for application of this feedback principle. A field trial of this system was made at Morristown, New Jersey, in which seventy of these amplifiers were operated in tandem. The results of this trial were highly satisfactory and demonstrated conclusively the correctness of the theory and the practicability of its commercial application.

INTRODUCTION

DUE TO advances in vacuum tube development and amplifier technique, it is now possible to secure any desired amplification of the electrical waves used in the communication field. When many amplifiers are worked in tandem, however, it becomes difficult to keep the overall circuit efficiency constant, variations in battery potentials and currents, small when considered individually, adding up to produce serious transmission changes for the overall circuit. Furthermore, although it has remarkably linear properties, when the modern vacuum tube amplifier is used to handle a number of carrier telephone channels, extraneous frequencies are generated which cause interference between the channels. To keep this interference within proper bounds involves serious sacrifice of effective amplifier capacity or the use of a push-pull arrangement which, while giving some increase in capacity, adds to maintenance difficulty.

However, by building an amplifier whose gain is deliberately made, say 40 decibels higher than necessary (10,000 fold excess on energy basis), and then feeding the output back on the input in such a way

* Presented at Winter Convention of A. I. E. E., New York City, Jan. 23-26, 1934. Published in *Electrical Engineering*, January, 1934.

¹ "Carrier in Cable" by A. B. Clark and B. W. Kendall, presented at the A. I. E. E. Summer Convention, Chicago, Ill., June, 1933; published in *Electrical Engineering*, July, 1933, and in *Bell Sys. Tech. Jour.*, July, 1933.

as to throw away the excess gain, it has been found possible to effect extraordinary improvement in constancy of amplification and freedom from non-linearity. By employing this feedback principle, amplifiers have been built and used whose gain varied less than 0.01 db with a change in plate voltage from 240 to 260 volts and whose modulation products were 75 db below the signal output at full load. For an amplifier of conventional design and comparable size this change in plate voltage would have produced about 0.7 db variation while the modulation products would have been only 35 db down; in other words, 40 db reduction in modulation products was effected. (On an energy basis the reduction was 10,000 fold.)

Stabilized feedback possesses other advantages including reduced delay and delay distortion, reduced noise disturbance from the power supply circuits and various other features best appreciated by practical designers of amplifiers.

It is far from a simple proposition to employ feedback in this way because of the very special control required of phase shifts in the amplifier and feedback circuits, not only throughout the useful frequency band but also for a wide range of frequencies above and below this band. Unless these relations are maintained, singing will occur, usually at frequencies outside the useful range. Once having achieved a design, however, in which proper phase relations are secured, experience has demonstrated that the performance obtained is perfectly reliable.

CIRCUIT ARRANGEMENT

In the amplifier of Fig. 1, a portion of the output is returned to the input to produce feedback action. The upper branch, called the μ -circuit, is represented as containing active elements such as an amplifier while the lower branch, called the β -circuit, is shown as a passive network. The way a voltage is modified after once traversing each circuit is denoted μ and β respectively and the product, $\mu\beta$, represents how a voltage is modified after making a single journey around amplifier and feedback circuits. Both μ and β are complex quantities, functions of frequency, and in the generalized concept either or both may be greater or less in absolute value than unity.²

Figure 2 shows an arrangement convenient for some purposes where, by using balanced bridges in input and output circuits, interaction between input and output is avoided and feedback action and amplifier impedances are made independent of the properties of circuits connected to the amplifier.

² μ is not used in the sense that it is sometimes used, namely, to denote the amplification constant of a particular tube, but as the complex ratio of the output to the input voltage of the amplifier circuit.

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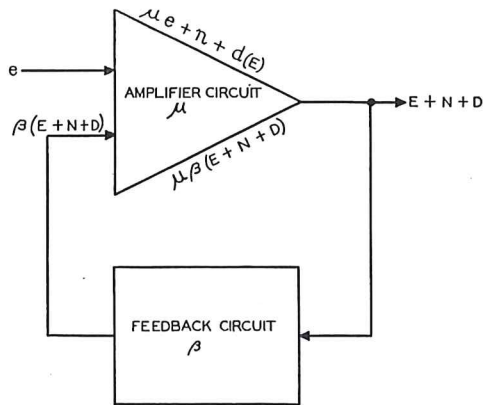


Fig. 1—Amplifier system with feedback.

- e —Signal input voltage.
- μ —Propagation of amplifier circuit.
- μe —Signal output voltage without feedback.
- n —Noise output voltage without feedback.
- $d(E)$ —Distortion output voltage without feedback.
- β —Propagation of feedback circuit.
- E —Signal output voltage with feedback.
- N —Noise output voltage with feedback.
- D —Distortion output voltage with feedback.

The output voltage with feedback is $E + N + D$ and is the sum of $\mu e + n + d(E)$, the value without feedback plus $\mu\beta[E + N + D]$ due to feedback.

$$E + N + D = \mu e + n + d(E) + \mu\beta[E + N + D]$$

$$[E + N + D](1 - \mu\beta) = \mu e + n + d(E)$$

$$E + N + D = \frac{\mu e}{1 - \mu\beta} + \frac{n}{1 - \mu\beta} + \frac{d(E)}{1 - \mu\beta}$$

If $|\mu\beta| \gg 1$, $E \doteq -\frac{e}{\beta}$. Under this condition the amplification is independent of μ but does depend upon β . Consequently the over-all characteristic will be controlled by the feedback circuit which may include equalizers or other corrective networks.

GENERAL EQUATION

In Fig. 1, β is zero without feedback and a signal voltage, e_0 , applied to the input of the μ -circuit produces an output voltage. This is made up of what is wanted, the amplified signal, E_0 , and components that are not wanted, namely, noise and distortion designated N_0 and D_0 and assumed to be generated within the amplifier. It is further assumed that the noise is independent of the signal and the distortion generator or modulation a function *only of the signal output*. Using the notation of Fig. 1, the output without feedback may be written as:

$$E_0 + N_0 + D_0 = \mu e_0 + n + d(E_0), \tag{1}$$

where zero subscripts refer to conditions without feedback.

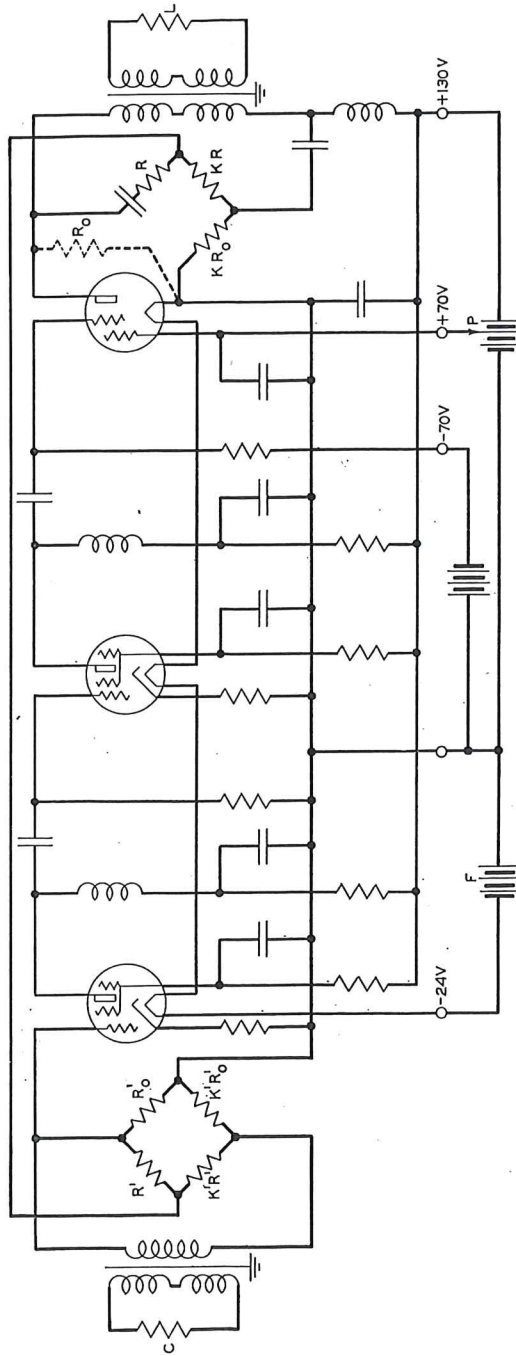


Fig. 2—Circuit of a negative feedback amplifier.

With feedback, β is not zero and the input to the μ -circuit becomes $e_0 + \beta(E + N + D)$. The output is $E + N + D$ and is equal to $\mu[e_0 + \beta(E + N + D)] + n + d(E)$ or:

$$E + N + D = \frac{\mu e_0}{1 - \mu\beta} + \frac{n}{1 - \mu\beta} + \frac{d(E)}{1 - \mu\beta}. \quad (2)$$

In the output, signal, noise and modulation are divided by $(1 - \mu\beta)$, and assuming $|1 - \mu\beta| > 1$, all are reduced.

CHANGE IN GAIN DUE TO FEEDBACK

From equation (2), the amplification with feedback equals the amplification without feedback divided by $(1 - \mu\beta)$. The effect of adding feedback, therefore, usually is to change the gain of the amplifier and this change will be expressed as:

$$G_{CF} = 20 \log_{10} \left| \frac{1}{1 - \mu\beta} \right|, \quad (3)$$

where G_{CF} is *db change in gain due to feedback*. $1/(1 - \mu\beta)$ will be used as a quantitative measure of the effect of feedback and the feedback referred to as *positive feedback* or *negative feedback* according as the absolute value of $1/(1 - \mu\beta)$ is greater or less than unity. Positive feedback increases the gain of the amplifier; negative feedback reduces it. The term *feedback* is not limited merely to those cases where the absolute value of $1/(1 - \mu\beta)$ is other than unity.

From $\mu\beta = |\mu\beta| \angle \Phi$ and (3), it may be shown that:

$$10^{-G_{CF}/10} = 1 - 2|\mu\beta| \cos \Phi + |\mu\beta|^2, \quad (4)$$

which is the equation for a family of concentric circles of radii $10^{-G_{CF}/10}$ about the point 1, 0. Figure 3 is a polar diagram of the vector field of $\mu\beta = |\mu\beta| \angle \Phi$. Using rectangular instead of polar coordinates, Fig. 4 corresponds to Fig. 3 and may be regarded as a diagram of the field of $\mu\beta$ where the parameter is db change in gain due to feedback. From these diagrams all of the essential properties of feedback action can be obtained such as change in amplification, effect on linearity, change in stability due to variations in various parts of the system, reduction of noise, etc. Certain significant boundaries have been designated similarly on both figures.

For example, boundary *A* is the locus of zero change in gain due to feedback. Along this parametric contour line where the absolute magnitude of amplification is not changed by feedback action, values of $|\mu\beta|$ range from zero to 2 and the phase shift, Φ , around the amplifier



Fig. 2—Circuit of a negative feedback amplifier.

and feedback circuits equals $\cos^{-1} |\mu\beta|/2$ and, therefore, lies between -90° and $+90^\circ$. For all conditions inside or above this boundary, the gain with feedback is increased; outside or below, the gain is decreased.

STABILITY

From equation (2), $\mu e_0/(1 - \mu\beta)$ is the amplified signal with feedback and, therefore, $\mu/(1 - \mu\beta)$ is an index of the amplification. It is of course a complex ratio. It will be designated A_F and referred to as the amplification with feedback.

To consider the effect of feedback upon stability of amplification, the stability will be viewed as the ratio of a change, δA_F , to A_F where δA_F is due to a change in either μ or β and the effects may be derived by assuming the variations are small.

$$A_F = \frac{\mu}{1 - \mu\beta}, \quad (5)$$

$$\left[\frac{\delta A_F}{A_F} \right]_{\mu} \doteq \frac{\left[\frac{\delta \mu}{\mu} \right]}{1 - \mu\beta}, \quad (6)$$

$$\left[\frac{\delta A_F}{A_F} \right]_{\beta} \doteq \frac{\mu\beta}{1 - \mu\beta} \left[\frac{\delta \beta}{\beta} \right]. \quad (7)$$

If $\mu\beta \gg 1$, it is seen that μ or the μ -circuit is stabilized by an amount corresponding to the reduction in amplification and the effect of introducing a gain or loss in the μ -circuit is to produce no material change in the overall amplification of the system; the stability of amplification as affected by β or the β -circuit is neither appreciably improved nor degraded since increasing the loss in the β -circuit raises the gain of the amplifier by an amount almost corresponding to the loss introduced and vice-versa. If μ and β are both varied and the variations sufficiently small, the effect is the same as if each were changed separately and the two results then combined.

In certain practical applications of amplifiers it is the change in gain or ammeter or voltmeter reading at the output that is a measure of the stability rather than the complex ratio previously treated. The conditions surrounding gain stability may be examined by considering the absolute value of A_F . This is shown as follows: Let (db) represent the gain in decibels corresponding to A_F . Then

$$\begin{aligned} (db) &= 20 \log_{10} |A_F|, \\ \delta(db) &\doteq 8.686 \left[\frac{\delta |A_F|}{|A_F|} \right]. \end{aligned} \quad (8)$$

To get the absolute value of the amplification: Let

$$\mu\beta = |\mu\beta| \angle \Phi, \tag{9}$$

$$|A_F| = \frac{|\mu|}{\sqrt{1 - 2|\mu\beta| \cos \Phi + |\mu\beta|^2}}. \tag{10}$$

The stability of amplification which is proportional to the gain stability is given by:

$$\left[\frac{\delta |A_F|}{|A_F|} \right]_{|\mu|} \doteq \frac{1 - |\mu\beta| \cos \Phi}{|1 - \mu\beta|^2} \left[\frac{\delta |\mu|}{|\mu|} \right], \tag{11}$$

$$\left[\frac{\delta |A_F|}{|A_F|} \right]_{|\beta|} \doteq \left| \frac{\mu\beta}{1 - \mu\beta} \right| \left[\frac{\cos \Phi - |\mu\beta|}{|1 - \mu\beta|} \right] \left[\frac{\delta |\beta|}{|\beta|} \right], \tag{12}$$

$$\left[\frac{\delta |A_F|}{|A_F|} \right]_{\Phi} \doteq - \left| \frac{\mu\beta}{1 - \mu\beta} \right| \left[\frac{\sin \Phi}{|1 - \mu\beta|} \right] [\delta \Phi]. \tag{13}$$

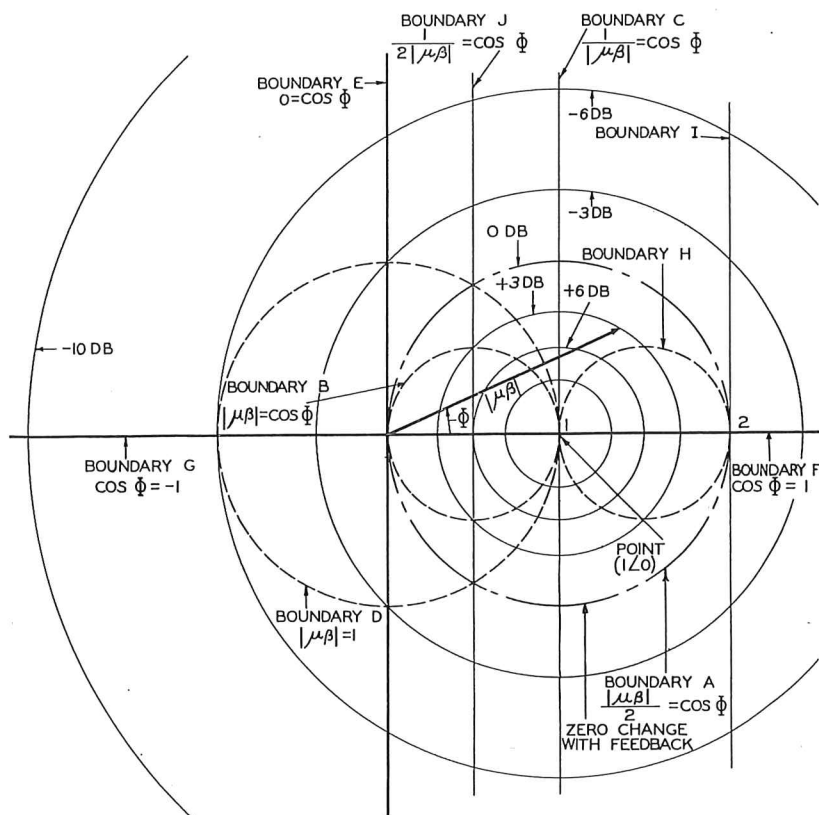


Fig. 3—The vector field of $\mu\beta$. See caption for Fig. 4.

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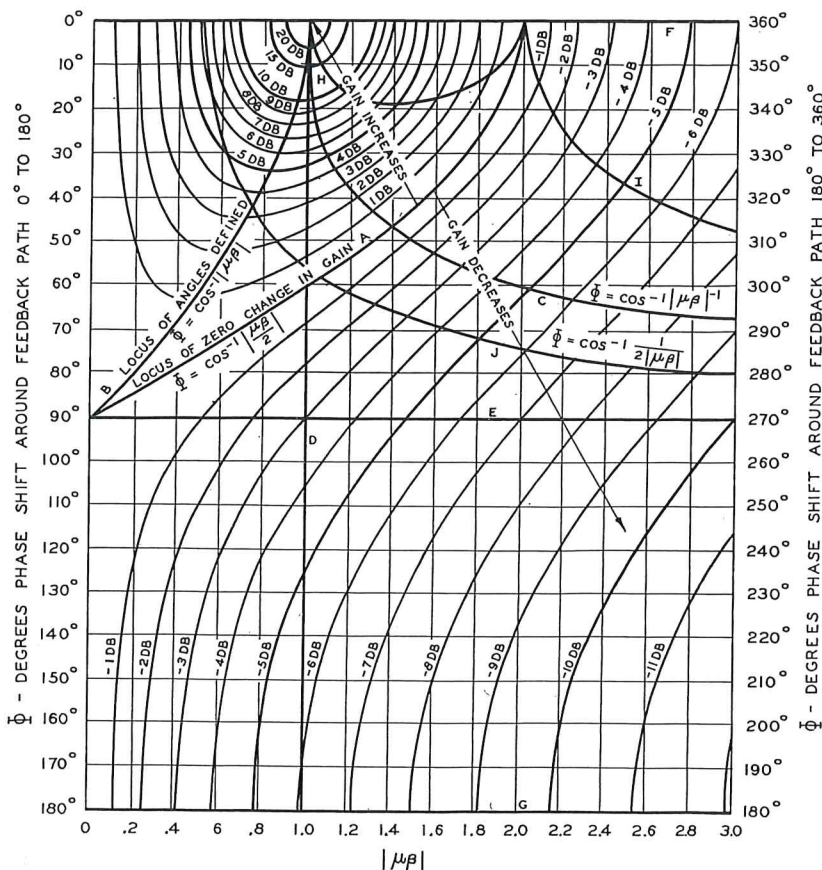


Fig. 4—Phase shift around the feedback path plotted as a function of $|\mu\beta|$, the absolute value of $\mu\beta$.

$\mu\beta$ is a complex quantity which represents the ratio by which the amplifier and feedback (or more generally μ and β) modify a voltage in a single trip around the closed path.

First, there is a set of boundary curves indicated as A, B, C, D, E, F, G, H, I, and J which gives either limiting or significant values of $|\mu\beta|$ and Φ .

Secondly, there is a family of curves in which db change in gain due to feedback is the parameter.

Boundaries

A. Conditions in which gain and modulation are unaffected by feedback.

B. Constant amplification ratio against small variations in $|\beta|$.

Constant change in gain, $\frac{1}{|1 - \mu\beta|}$, against variations in $|\mu|$ and $|\beta|$.

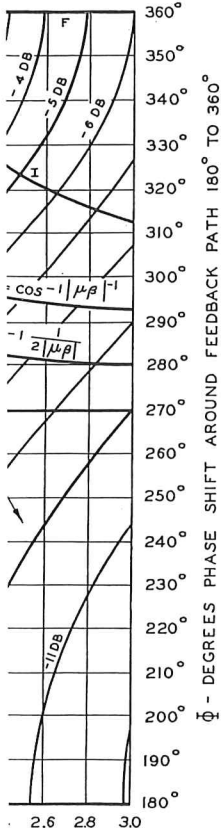
Stable phase shift through the amplifier against variations in Φ_β .

The boundary on which the stability of amplification is unaffected by feedback.

C. Constant amplification ratio against small variations in $|\mu|$.

Constant phase shift through the amplifier against variations in Φ_μ .

The absolute magnitude of the voltage fed back $\frac{|\mu\beta|}{|1 - \mu\beta|}$ is constant against variations in $|\mu|$ and $|\beta|$.



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A curious fact to be noted from (11) is that it is possible to choose a value of $\mu\beta$ (namely, $|\mu\beta| = \sec \Phi$) so that the numerator of the right hand side vanishes. This means that the gain stability is perfect, assuming differential variations in $|\mu|$. Referring to Figs. 3 and 4, contour C is the locus of $|\mu\beta| = \sec \Phi$ and it includes all amplifiers whose gain is unaffected by small variations in $|\mu|$. In this way it is even possible to stabilize an amplifier whose feedback is positive, i.e., feedback may be utilized to raise the gain of an amplifier and, at the same time, the gain stability with feedback need not be degraded but on the contrary improved. If a similar procedure is followed with an amplifier whose feedback is negative, the gain stability will be theoretically perfect and independent of the reductions in gain due to feedback. Over too wide a frequency band practical difficulties will limit the improvements possible by these methods.

With negative feedback, gain stability is always improved by an amount at least as great as corresponds to the reduction in gain and generally more; with positive feedback, gain stability is never degraded by more than would correspond to the increase in gain and under appropriate conditions, assuming the variations are not too great, is as good as or much better than without feedback. With positive feedback, the variations in μ or β must not be permitted to become sufficiently great to cause the amplifier to sing or give rise to instability as defined in a following section on "Avoiding Singing."

MODULATION

To determine the effect of feedback action upon modulation produced in the amplifier circuit, it is convenient to assume that the output of undistorted signal is made the same with and without feedback and that a comparison is then made of the difference in modulation with and without feedback. Therefore, with feedback, the input is changed to $e = e_0(1 - \mu\beta)$ and, referring to equation (2), the output voltage is μe_0 , and the generated modulation, $d(E)$, assumes its value without feedback, $d(E_0)$, and $d(E)/(1 - \mu\beta)$ becomes $d(E_0)/(1 - \mu\beta)$ which is $D_0/(1 - \mu\beta)$. This relationship is approximate because the

- D. $|\mu\beta| = 1$.
- E. $\Phi = 90^\circ$. Improvement in gain stability corresponds to twice db reduction in gain.
- F and G. Constant amplification ratio against variations in Φ .
- H. Same properties as B.
- I. Same properties as E.
- J. Conditions in which $\frac{|\mu|}{|1 - \mu\beta|} = \frac{-1}{|\beta|}$ the overall gain is the exact negative inverse of the transmission through the β -circuit.

voltage at the input without feedback is free from distortion and with feedback it is not and, hence, the assumption that the generated modulation is a function *only of the signal output* used in deriving equation (2) is not necessarily justified.

From the relationship $D = D_0/(1 - \mu\beta)$, it is to be concluded that modulation with feedback will be reduced db for db as the effect of feedback action causes an arbitrary db reduction in the gain of the amplifier, i.e., when the feedback is negative. With positive feedback the opposite is true, the modulation being increased by an amount corresponding to the increase in amplification.

If modulation in the β -circuit is a factor, it can be shown that usually in its effect on the output, the modulation level at the output due to non-linearity of the β -circuit is approximately $\mu\beta/(1 - \mu\beta)$ multiplied by the modulation generated in the β -circuit acting alone and without feedback.

ADDITIONAL EFFECTS

Noise

A criterion of the worth of a reduction in noise is the reduction in signal-to-noise ratio at the output of an amplifier. Assuming that the amount of noise introduced is the same in two systems, for example with and without feedback respectively, and that the signal outputs are the same, a comparison of the signal-to-noise ratios will be affected by the amplification between the place at which the noise enters and the output. Denoting this amplification by a and a_0 respectively, it can be shown that the relation between the two noise ratios is $(a_0/a)(1 - \mu\beta)$. This is called the *noise index*.

If noise is introduced in the power supply circuits of the last tube, $a_0/a = 1$ and the noise index is $(1 - \mu\beta)$. As a result of this relation less expensive power supply filters are possible in the last stage.

Phase Shift, Envelope Delay, Delay Distortion

In the expression $A_F = [\mu/(1 - \mu\beta)] \lfloor \theta$, θ is the overall phase shift with feedback, and it can be shown that the *phase shift through the amplifier with feedback may be made to approach the phase shift through the β -circuit plus 180 degrees*. The effect of phase shift in the β -circuit is not correspondingly reduced. It will be recalled that in reducing the change in phase shift with frequency, envelope delay, which is the slope of the phase shift with respect to the angular velocity, $\omega = 2\pi f$, also is reduced. The *delay distortion* likewise is reduced because a measure of delay distortion at a particular frequency is the difference between the envelope delay at that frequency and the least envelope delay in the band.

β-Circuit Equalization

Referring to equation (2), the output voltage, E , approaches $-e_0/\beta$ as $1 - \mu\beta \doteq -\mu\beta$ and equals it in absolute value if $\cos \Phi = \frac{1}{2|\mu\beta|}$ where $\mu\beta = |\mu\beta| \angle \Phi$. Under these circumstances increasing the loss in the β -circuit one db raises the gain of the amplifier one db and vice-versa, thus giving any gain-frequency characteristic for which a like loss-frequency characteristic can be inserted in the β -circuit. This procedure has been termed β -circuit equalization. It possesses other advantages which cannot be dwelt upon here.

AVOID SINGING

Having considered the theory up to this point, experimental evidence was readily acquired to demonstrate that $\mu\beta$ might assume large values,

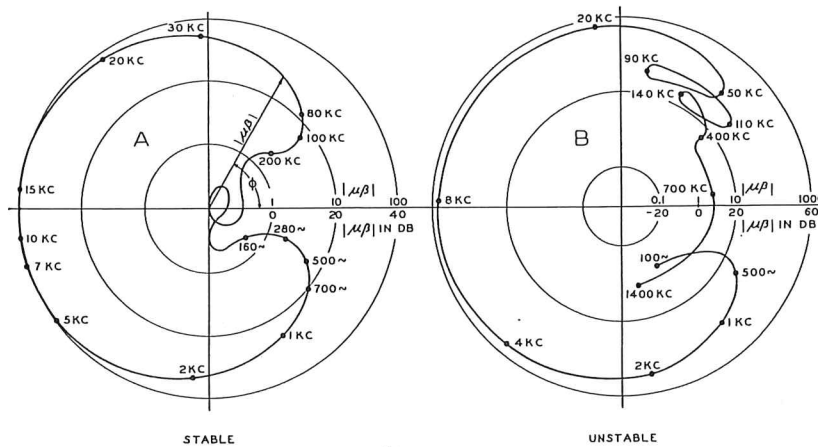


Fig. 5—Measured $\mu\beta$ characteristics of two amplifiers.

for example 10 or 10,000, provided Φ was not at the same time zero. However, one noticeable feature about the field of $\mu\beta$ (Figs. 3 and 4) is that it implies that even though the phase shift is zero and the absolute value of $\mu\beta$ exceeds unity, self-oscillations or singing will not result. This may or may not be true. When the author first thought about this matter he suspected that owing to practical non-linearity, singing would result whenever the gain around the closed loop equalled or exceeded the loss and simultaneously the phase shift was zero, i.e., $\mu\beta = |\mu\beta| + j0 \geq 1$. Results of experiments, however, seemed to indicate something more was involved and these matters were described to Mr. H. Nyquist, who developed a more general criterion

for freedom from instability³ applicable to an amplifier having linear positive constants.

To use this criterion, plot $\mu\beta$ (the modulus and argument vary with frequency) and its complex conjugate in polar coordinates for all values of frequency from 0 to $+\infty$. If the resulting loop or loops do not enclose the point (1, 0) the system will be stable, otherwise not.³ The envelope of the transient response of a stable amplifier

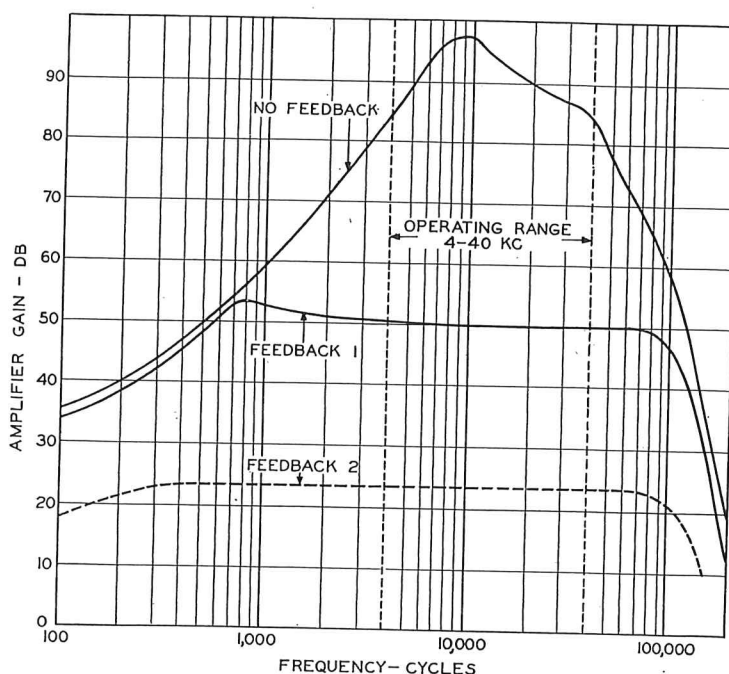


Fig. 6—Gain frequency characteristics with and without feedback of amplifier of Fig. 2.

always dies away exponentially with time; that of an unstable amplifier in all physically realizable cases increases with time. Characteristics *A* and *B* in Fig. 5 are results of measurements on two different amplifiers; the amplifier having $\mu\beta$ -characteristic denoted *A* was stable; the other unstable.

The number of stages of amplification that can be used in a single amplifier is not significant except insofar as it affects the question of avoiding singing. Amplifiers with considerable negative feedback

³For a complete description of the criterion for stability and instability and exactly what is meant by enclosing the point (1, 0), reference should be made to "Regeneration Theory"—H. Nyquist, *Bell System Technical Journal*, Vol. XI, pp. 126-147, July, 1932.

have been tested where the number of stages ranged from one to five inclusive. In every case the feedback path was from the output of the last tube to the input of the first tube.

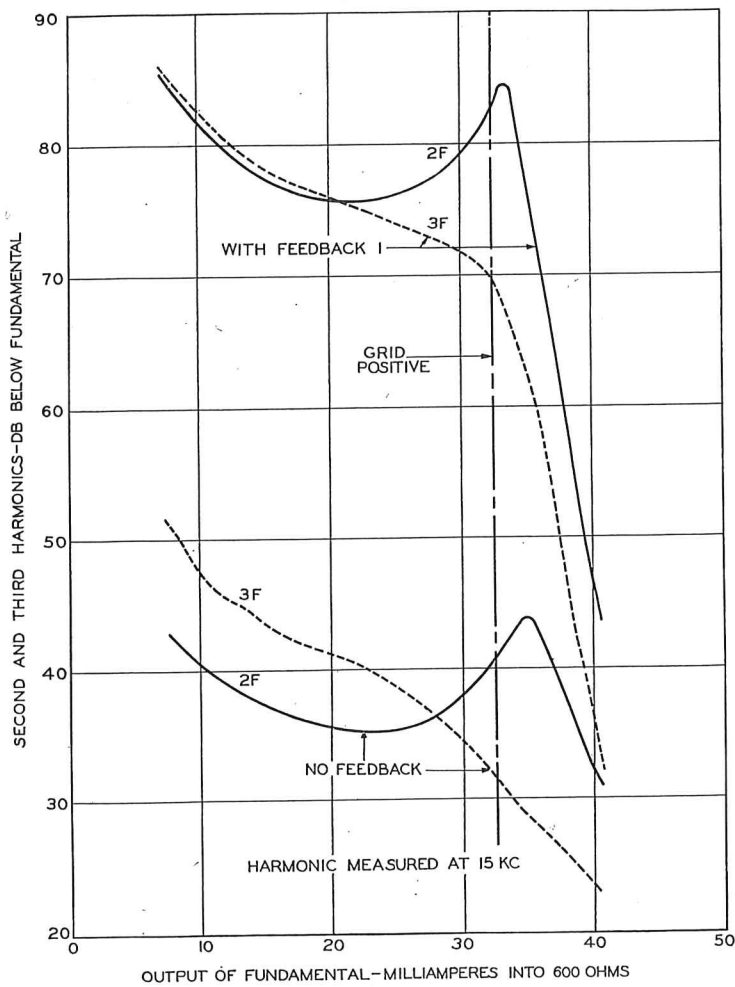


Fig. 7—Modulation characteristics with and without feedback for the amplifier of Fig. 2.

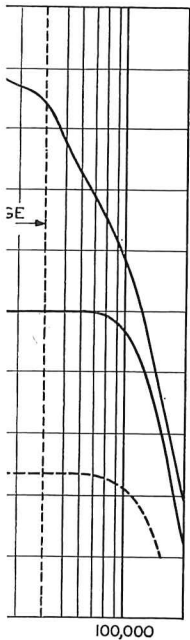
EXPERIMENTAL RESULTS

Figures 6 and 7 show how the gain-frequency and modulation characteristics of the three-stage impedance coupled amplifier of Fig. 2 are improved by negative feedback. In Fig. 7, the improvement in harmonics is not exactly equal to the db reduction in gain. Figure 8

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shows measurements on a different amplifier in which harmonics are reduced as negative feedback is increased, db for db over a 65 db range.

That the gain with frequency is practically independent of small variations in $|\mu|$ is shown by Fig. 9. This is a characteristic of the Morristown amplifier described in the paper by Messrs. Clark and Kendall¹ which meets the severe requirements imposed upon a repeater amplifier for use in cable carrier systems. Designed to amplify frequencies from 4 kc

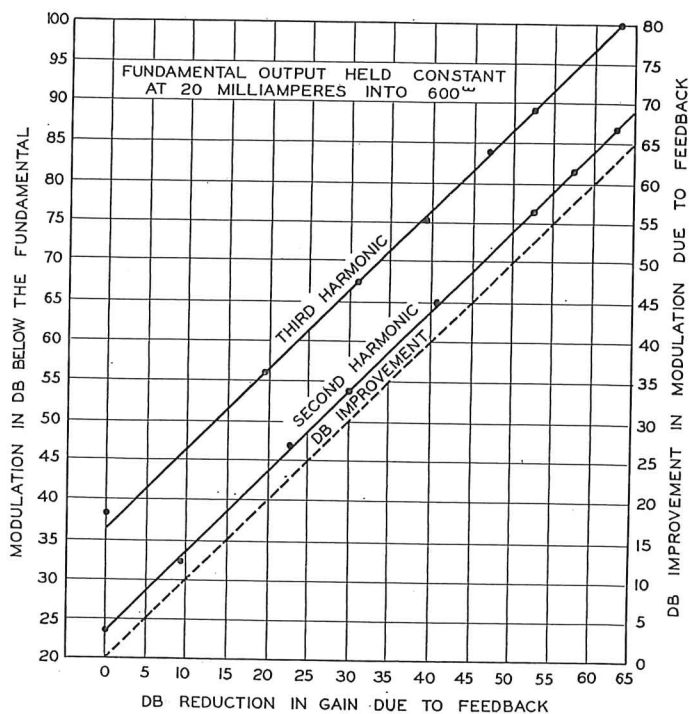
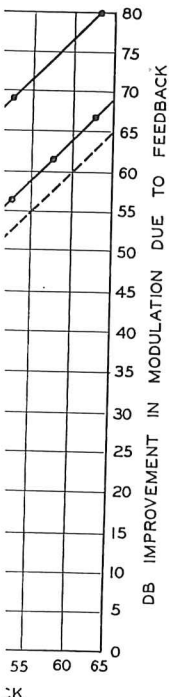


Fig. 8—Improvement of harmonics with feedback. One example of another amplifier in which with 60 db feedback, harmonic currents in the output are only one-thousandth and their energy one-millionth of the values without feedback.

to 40 kc the maximum change in gain due to variations in plate voltage does not exceed 7/10000 db per volt and at 20 kc the change is only 1/20000 db per volt. This illustrates that for small changes in $|\mu|$, the ratio of the stability without feedback to the stability with feedback, called the *stability index*, approaches $|1 - \mu\beta|^2 / (1 - |\mu\beta| \cos \Phi)$ and gain stability is improved at least as much as the gain is reduced and usually more and is theoretically perfect if $\cos \Phi = 1/|\mu\beta|$.

¹Loc. cit.

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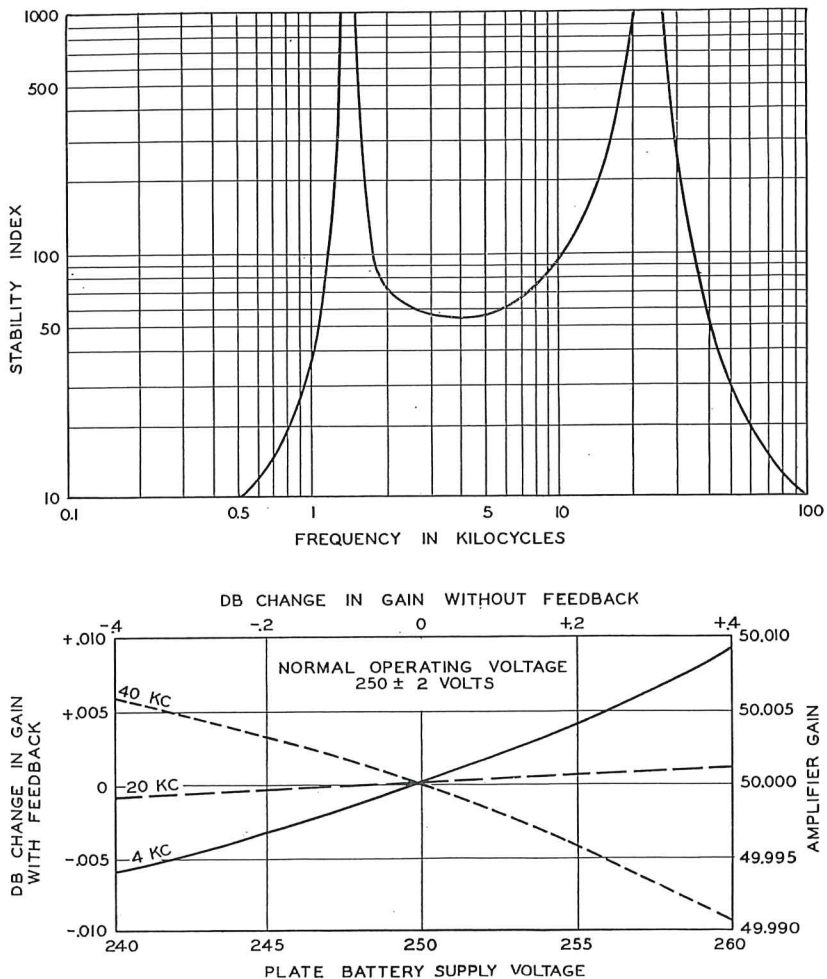


Fig. 9—Representative gain stability of a single amplifier as determined by measuring 69 feedback amplifiers in tandem at Morristown, N. J.
 The upper figure shows the absolute value of the stability index. It can be seen that between 20 and 25 kc the improvement in stability is more than 1000 to 1 yet the reduction in gain was less than 35 db.
 The lower figure shows change in gain of the feedback amplifier with changes in the plate battery voltage and the corresponding changes in gain without feedback. At some frequencies the change in gain is of the same sign as without feedback and at others it is of opposite sign and it can be seen that near 23 kc the stability must be perfect.

Figure 10 indicates the effectiveness with which the gain of a feedback amplifier can be made independent of variations in input amplitude up to practically the overload point of the amplifier. These measurements were made on a three-stage amplifier designed to work from 3.3 kc to 50 kc.

Figure 11 shows that negative feedback may be used to improve phase shift and reduce delay and delay distortion. These measurements

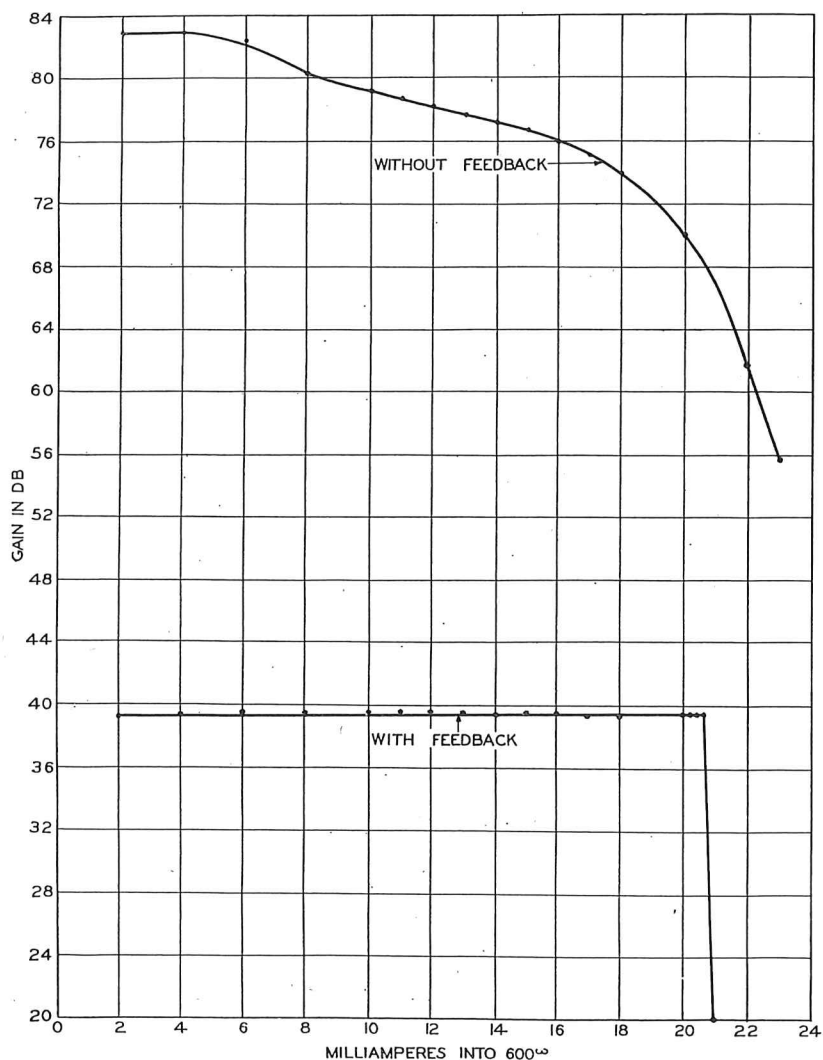


Fig. 10—Gain-load characteristic with and without feedback for a low level amplifier designed to amplify frequencies from 3.5 to 50 kc.

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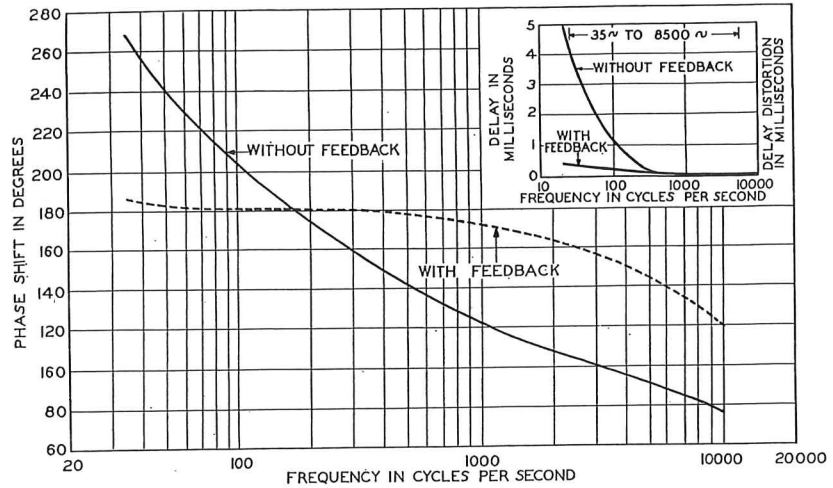
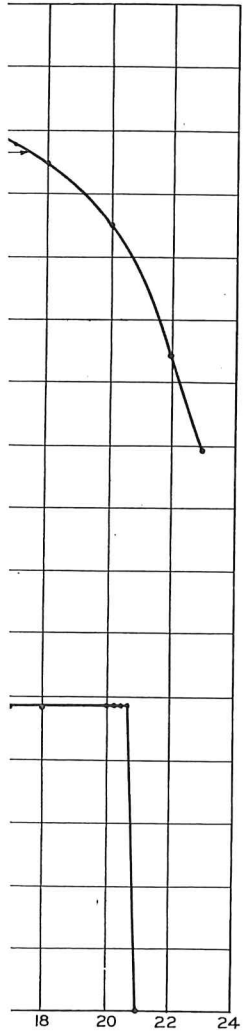


Fig. 11—Phase shift, delay, and delay distortion with and without feedback for a single tube voice frequency amplifier.

were made on an experimental one-tube amplifier, 35–8500 cycles, feeding back around the low side windings of the input and output transformers.

Figure 12 gives the gain-frequency characteristic of an amplifier with and without feedback when in the β -circuit there was an equalizer

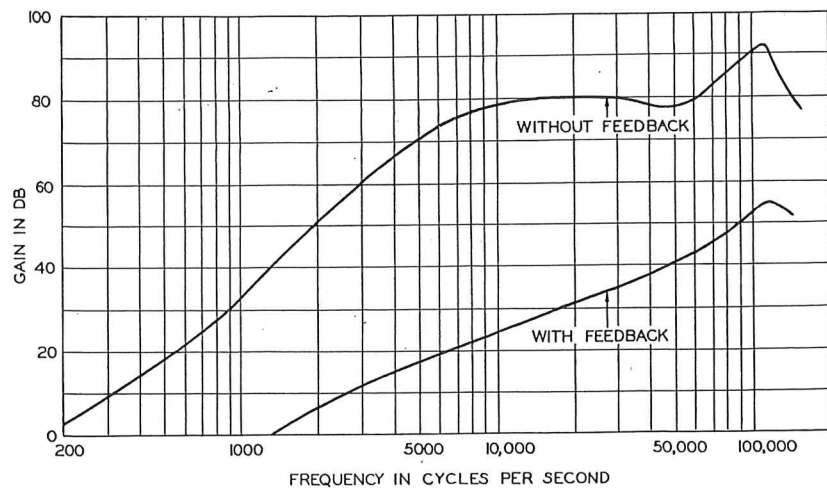


Fig. 12—Gain-frequency characteristic of an amplifier with an equalizer in the β -circuit. This was designed to have a gain frequency characteristic with feedback of the same shape as the loss frequency characteristic of a non-loaded telephone cable.

for a low level amplifier
50 kc.

designed to make the gain-frequency characteristic of the amplifier with feedback of the same shape as the loss-frequency characteristic of a non-loaded telephone cable.

CONCLUSION

The feedback amplifier dealt with in this paper was developed primarily with requirements in mind for a cable carrier telephone system, involving many amplifiers in tandem with many telephone channels passing through each amplifier. Most of the examples of feedback amplifier performance have naturally been drawn from amplifiers designed for this field of operation. In this field, vacuum tube amplifiers normally possessing good characteristics with respect to stability and freedom from distortion are made to possess superlatively good characteristics by application of the feedback principle.

However, certain types of amplifiers in which economy has been secured by sacrificing performance characteristics, particularly as regards distortion, can be made to possess improved characteristics by the application of feedback. Discussion of these amplifiers is beyond the scope of this paper.