

Nov. 26, 1940.

F. B. ANDERSON

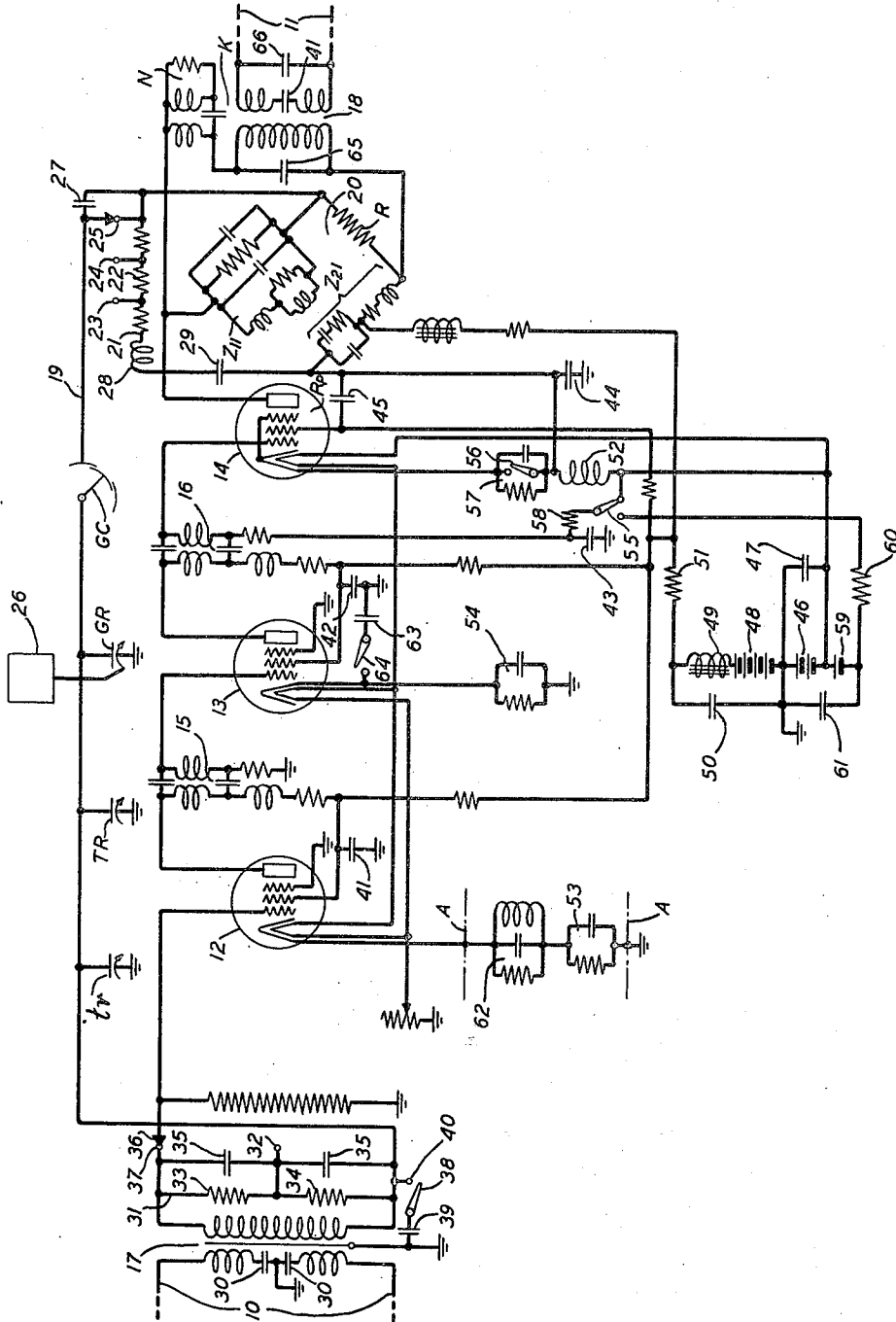
2,223,161

NEGATIVE FEEDBACK AMPLIFIER CIRCUIT

Filed Aug. 5, 1939

2 Sheets-Sheet 1

FIG. 1



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FIG. 2

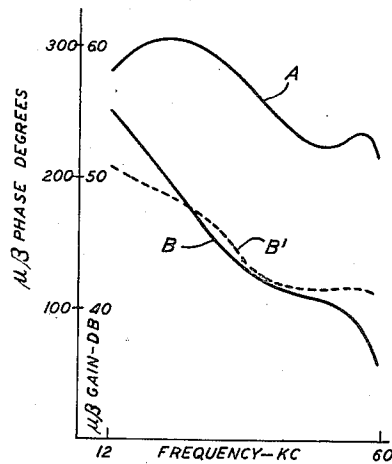


FIG. 3

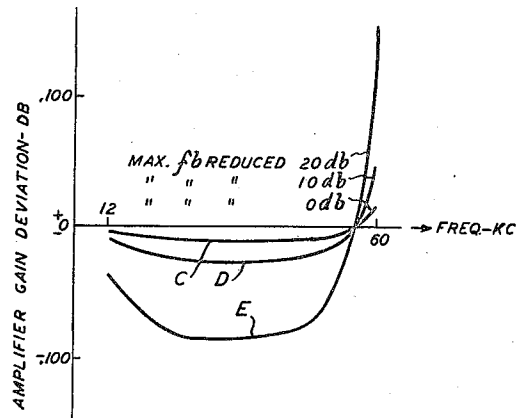


FIG. 4

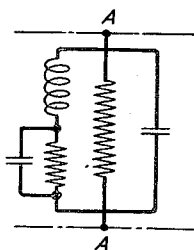


FIG. 5

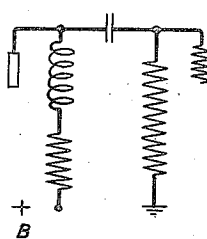
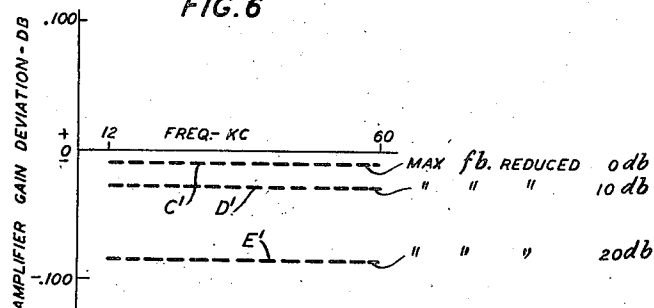


FIG. 6



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2,223,161

NEGATIVE FEEDBACK AMPLIFIER CIRCUIT

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4 Claims. (Cl. 179—171)

This invention relates to electron discharge device circuits and more particularly to a negative feedback amplifier circuit of the general type disclosed in H. S. Black Patent 2,102,671, issued December 21, 1937.

It has been observed that when gain-reducing negative feedback amplifiers are operated with an amount of feedback less than infinite feedback or, from the practical standpoint, maximum feedback for the particular amplifier, that the amplifier gain over the operating band or range of the amplifier does not differ uniformly from the amplifier gain for the infinite feedback condition. Not only is there a non-uniform deviation over the frequency range, but as the departure in the amount of actual feedback below infinite feedback increases, the deviation increases and becomes more non-uniform with frequency over the frequency range. In the case of an amplifier in a transmission line, having gain regulator means associated therewith for regulating the amplifier gain manually, or automatically, or both, with variations in transmission conditions, this means that for preassigned regulator settings for preassigned amounts of feedback or, conversely, amplifier gain, the expected amplifier gain down so many decibels from maximum gain for the amplifier over the operating band is not realized. This deviation effect has come to be referred to by those skilled in the art as "the $\mu\beta$ -effect."

It is an object of this invention to compensate or correct for this deviation effect so that the deviation, if any, for preassigned feedback levels below infinite feedback will be constant over the operating frequency range of the amplifier.

In accordance with the invention, the feedback loop phase-frequency characteristic curve of the amplifier is modified at the sacrifice of some reduction in the possible maximum feedback loop gain for the amplifier. This is done to satisfy the requirement that, if the deviations in amplifier gain at one frequency for two values of feedback loop gain, or $|\mu\beta|$, are to be in the same ratio as those at another frequency for two values of $|\mu\beta|$ of the same ratio as the first pair, the following relation should hold:

$$\frac{k|\mu\beta|_1}{k|\mu\beta|_2} = \frac{\cos \varphi_1 - \frac{1}{2|\mu\beta|_1 \cos \varphi_1}}{\cos \varphi_2 - \frac{1}{2|\mu\beta|_2 \cos \varphi_2}}$$

where $|\mu\beta|_1$ is equal to $|\mu\beta|$ at a frequency of f_1 ; $|\mu\beta|_2$, to $|\mu\beta|$ at a frequency f_2 ; $k|\mu\beta|_1$ and $k|\mu\beta|_2$, to a constant times $|\mu\beta|_1$ and $|\mu\beta|_2$, respectively; φ_1 ,

to the phase angle of $|\mu\beta|_1$ and $k|\mu\beta|_1$; and φ_2 , to the phase angle of $|\mu\beta|_2$ and $k|\mu\beta|_2$.

This relation may be well approximated for $|\mu\beta|_1 \cos \varphi_1$ and $|\mu\beta|_2 \cos \varphi_2$, of the order of 10 or more, by neglecting the last fractional ratio. This gives:

$$\frac{|\mu\beta|_1}{|\mu\beta|_2} = \frac{\cos \varphi_1}{\cos \varphi_2}$$

A more complete understanding of the invention will be obtained from the detailed description which follows, taken in conjunction with the appended drawings, wherein:

Fig. 1 shows the circuit of a negative feedback amplifier;

Fig. 2 shows, in the solid lines, typical $\mu\beta$ -gain versus frequency and $\mu\beta$ -phase versus frequency curves for the amplifier of Fig. 1, and, in the broken line, the $\mu\beta$ -phase versus frequency curve necessary, in accordance with the invention, to compensate for $\mu\beta$ -effect if such $\mu\beta$ -gain versus frequency characteristic is to be obtained;

Fig. 3 shows amplifier gain deviation versus frequency curves for different values of feedback below maximum feedback for the amplifier;

Figs. 4 and 5 show networks that, in accordance with the invention, might be substituted for the networks shown between points A—A and for the first interstage network, respectively, of the amplifier of Fig. 1; and

Fig. 6 shows amplifier gain deviation versus frequency curves corresponding to those of Fig. 3, but evidencing the effect of modifying the amplifier of Fig. 1 in accordance with the invention.

The wave transmission system of Fig. 1 comprises a negative feedback amplifier generally similar to that of the copending application of F. B. Anderson et al., Serial No. 202,180, filed April 15, 1938, now Patent No. 2,170,046 Aug. 22, 1939, for Negative feedback amplifiers, and is adapted for use as a line amplifier for amplifying carrier frequency currents transmitted over a nineteen-gauge non-loaded cable circuit comprising an incoming line 10 and an outgoing line 11.

The amplifier comprises a plurality of electron discharge devices 12, 13, 14, for example, suppressor grid type tubes, connected in cascade by interstage networks 15, 16. These networks comprise impedance coupling networks including series capacities and shunt inductances and resistances. The amplifier further comprises an input transformer 17, an output transformer 18, a negative feedback path or connection 19, and an

output bridge 20. The bridge connects the plate circuit of the tube 14 to the feedback path or circuit and to the output transformer in the general manner disclosed, for example, in Fig. 65 of H. S. Black Patent 2,102,671, issued December 21, 1937, or in A. L. Stillwell Patent 1,993,758, issued March 12, 1935, and serves as a transmission equalizer of the constant resistance type as explained in these patents, particularly the Stillwell patent. The feedback path is in one diagonal of the bridge; the output transformer is in another. The remaining four arms are constituted by the plate resistance R_p of the tube 14, a resistance R , and two inverse impedances Z_{11} and Z_{21} .

The feedback through the path 19 reduces the amplifier gain but gives great improvement in quality and stability and greatly reduces harmonic distortion. It includes a flat gain control potentiometer 21 including a potentiometer resistance 22 having taps 23, 24, 25. A condenser potentiometer of the type disclosed in F. B. Anderson et al. Patent 2,106,336, issued January 25, 1938, is also included in the feedback path. This condenser potentiometer comprises a flat gain control condenser GC, a flat gain regulator condenser GR, and two trimmer condensers TR and *tr*. The condenser GC serves to vary, under manual adjustment, the amount of feedback to adjust the flat gain of the amplifier through a range of, for example, 10 decibels. The condenser GR may be automatically operated, for example, by a pilot wire gain regulator system 26 such as that disclosed in F. A. Brooks Patent 2,075,775, issued April 6, 1937, for varying the amount of feedback, for example, over a range of 14 decibels, to compensate for the flat portion of the variations in the line loss with line temperature.

The potentiometer 21 also comprises a condenser 27, an inductance 28, and a blocking condenser 29. The condenser 27 and inductance 28 improve the high frequency phase margin of the amplifier against singing, for potentiometer settings on taps 23 and 24, and inductance 28 improves the high frequency margin for tap setting 25. The tapped resistance 22 supplies uniform losses over the 12-60 kilocycle band in the feedback loop, the capacity 27 and inductance 28 having little effect in that frequency range; capacity 27 contributes phase margin at high frequencies above that range, and inductance 28 in the shunt arm of the potentiometer neutralizes some of the capacity bridging this arm and further improves the phase shift.

The amplifier is coupled to the incoming line 10 through the transformer 17, and to the outgoing line 11 through the transformer 18. The condensers 30 and condenser 41 in the line windings of the transformers serve to make the amplifier impedances more nearly match the cable impedance and to make the line circuits of the amplifier open circuit to direct current used, for example, for cable tests. The condensers, moreover, contribute loss for frequencies below the 12-60 kilocycle band, to facilitate meeting the requirement that the amplifier gain be considerably less than the cable attenuation at these low frequencies for all gain settings of the amplifier. Condensers 30, having equal capacities and their junction connected to ground, also increase the longitudinal balance of the system. A resistance 31, having a tap 32, dividing it into two portions 33, 34 and each having a condenser 35 in shunt therewith, is connected across the secondary of

the input transformer. A movable contact 36 connected to the control grid of the discharge device 12 may be connected to tap 32 for reducing the flat gain of the amplifier. These condensers 35 and the distributed capacity inherent in the secondary reduce any unfavorable high frequency phase shift that, especially with the contact 36 on the tap 32, the transformer 17 and its terminations introduce in transmission around the feedback loop, thus increasing the singing margin or the stability of the amplifier against self-oscillation at frequencies above the 12-60 kilocycle band. With the contact 36 on terminal 32, a switch 38 may be closed to connect condenser 39 between the grounded shield of transformer 17 and terminal 40. This condenser serves to compensate for the effect of the capacity to ground associated with terminal 37 so as to make the gain change due to a change in the setting of the GR condenser the same as it is with contact 36 on tap 37 and switch 38 open.

Condensers 41, 42, 43, 44 and 45 are blocking or by-pass condensers, each of negligible reactance in the pass band of the amplifier. Current for the heaters of the tubes is supplied from battery 46, by-passed by condenser 47 for reducing cross-talk between amplifiers to which this battery may be common. Plate and screen grid potentials for the tubes 12, 13 are supplied from battery 48 and a low-pass filter comprising choke 49 and condenser 50, through resistor 51 which serves to reduce cross-talk between amplifiers to which the battery may be common. Plate and screen potential for tube 14 is supplied by batteries 46 and 48 in series, the choke coil 52 in the cathode lead of tube 14 reducing alternating current flow through the battery. The cathode heating and space current supply system is of the general type disclosed in the copending application of J. O. Edson et al., Serial No. 82,156, filed May 27, 1936, now Patent No. 2,191,167 Feb. 20, 1940. Biasing potential for the control grid of tube 12 is obtained principally from the voltage drop across the network 53 in the cathode lead of that tube, this network comprising a biasing resistor and a by-pass condenser of low reactance in the 12-60 kilocycle band. A similar network 54 is provided in the cathode lead of the tube 13. With switches 55 and 56 in the positions shown in the drawings, biasing potential for the grid of tube 14 is obtained from voltage drop across the network 57 and the coil 52, connected in series in the cathode lead of the tube 14. The network 57 comprises a resistance shunted by a condenser of high reactance in the frequency range of the amplifier, the coil 52 being by-passed by the condenser 44, and the biasing potential is filtered by the resistance 58 and condenser 43. If switch 56 should be closed so as to short-circuit the network 57, the proper bias for the control grid of tube 14 is obtained by connecting the switch 55 to its other contact to provide a grid biasing battery 59 in series with a resistance 60. Condenser 61 limits the impedance common to the biasing circuits of several amplifiers such as the one shown and thus holds cross-talk, because of such coupling, within assigned limits.

The network 62 in the cathode lead of tube 12 furnishes local negative feedback around the tube, for improving the singing margin of the amplifier, in accordance with D. D. Robertson Patent 1,994,486, issued March 19, 1935.

Network 54, which can be by-passed by a condenser 63 of negligible reactance in the trans-

mission band by closure of the switch 64, and the network 57, which can be short-circuited by closure of switch 56, facilitate obtaining phase and gain conditions for transmission around the feedback loop that avoid singing for all adjustments of the movable contact of the potentiometer 21 on the taps 23, 24, 25. For a given setting of the condensers GC and GR, the flat gain of the amplifier is at its maximum value when the contact is on tap 23, with contact 36 on terminal 37 of the transformer 17 and the switches 56 and 64 closed. For a gain reduction from this maximum, the movable contact of potentiometer 21 is adjusted to tap 24 and the switch 64 is opened. For a further gain reduction, the movable contact is adjusted to tap 25 and the switch 56 is opened and switch 55 is as shown. A still further gain reduction is obtained by moving contact 36 to tap 32 with switch 38 closed.

The output bridge should not only have suitable transmission and impedance properties in the operating band of the amplifier, but it should have favorable phase properties for the feedback loop above the band notwithstanding the high generator impedance of the tube 14. In accordance with the disclosure of the copending application of Anderson et al., Serial No. 202,180, filed April 15, 1938, with the constant resistance output bridge configuration, a satisfactory high frequency phase characteristic is obtained by associating with the load, including the output transformer 18 and the associated shunt capacities 65, 66, a network N to render the receiving impedance (i. e., the impedance of the bridge arm constituting the load) a substantially constant resistive impedance over not only the operating frequency band, but also a wide frequency range above that band. In the drawing, that bridge arm is designated K and the network N is shown connected in serial relation with the primary winding of the transformer 18, between the plate of tube 14 and the primary winding. The high impedance R_p of the tube 14 accentuates difficulties that the transformer and bridge constants contribute to stabilizing the feedback loop against oscillation at frequencies above the operating frequency band. Such difficulties, however, are overcome by network N, which builds the transformer with its associated capacitances 65, 66 out to a network K which has a constant resistance impedance.

In Fig. 2, the solid line curves A and B are typical maximum feedback or $\mu\beta$ -gain versus frequency and $\mu\beta$ -phase versus frequency characteristic curves for an amplifier of the type described. Whether the amplifier operates at the condition of maximum feedback, i. e., maximum $\mu\beta$ -gain, is determined by the setting of the gain-regulating means in the feedback loop. It might be expected that, if the gain-regulating means in the feed-back loop is adjusted so that the amount of feedback is less than the maximum possible, at the reduced feedback the gain of the amplifier would be equally spaced or altered by the same amount from the gain at maximum feedback for all frequencies in the operating band of the amplifier. This, however, is not the case. In Fig. 3, curves C, D, E show the deviation from the ideal or expected amplifier gain for feedback regulator settings for various amounts of feedback reduced below the maximum feedback. Of course, in the ideal case of infinite feedback, there would be no deviation whatever. As a practical matter, however, the maximum feedback obtainable in the particular amplifier will not be

infinite in value but finite. Nevertheless, as Fig. 3 shows, the deviation will be the least for the condition of maximum feedback, and becomes more pronounced and more non-uniform with frequency as the actual feedback is reduced more and more below the maximum. This effect has come to be designated by those working in the negative feedback amplifier field the " $\mu\beta$ -effect," and compensation or correction for this effect is an object of the invention.

An explanation of this so-called $\mu\beta$ -effect is suggested by the following analysis. In accordance with the mathematical treatment of negative feedback amplifiers in Black 2,102,671, let the electromotive force applied at the input to the amplifier be considered equal to e , and the potential actually effective on the control grid of the first stage because of the input e and the energy fed back from the output stage be considered equal to V . Then, if the amplification of the amplifier in its forward path is denominated μ , and the fraction of the output fed back be denominated β ,

$$e + \mu\beta V = V \quad (1)$$

$$V = \frac{e}{1 - \mu\beta} \quad (2)$$

If μ_F = amplification with feedback =

$$\frac{\mu V}{e} = \frac{\mu e}{e(1 - \mu\beta)} = \frac{\mu}{1 - \mu\beta} \quad (3)$$

then

$$\mu_F = \frac{\mu}{(1 - \mu\beta)} = \frac{-\frac{1}{\beta}}{1 - \frac{1}{\mu\beta}} = -\frac{1}{\beta} \left(\frac{1}{1 - \frac{1}{\mu\beta}} \right) \quad (4)$$

If $\mu\beta$ is equal to infinity μ_F becomes equal to

$$-\frac{1}{\beta}$$

Equation 4 shows that the factor

$$\left(\frac{1}{1 - \frac{1}{\mu\beta}} \right)$$

represents the deviation from the ideal

$$-\frac{1}{\beta}$$

realized with infinite feedback ($\mu\beta = \infty$). The deviation factor is a complex quantity since $\mu\beta$ is a complex quantity, hence, the deviation factor should be written as

$$\frac{1}{1 - \frac{1}{|\mu\beta|/\varphi}} \quad (5)$$

It will be at a minimum and less than unity for $\varphi = \pi$; a maximum and greater than unity for $\varphi = 0$; and will approximate unity for φ in the region of $\pi/2$ or $3\pi/2$ for $|\mu\beta| \gg 1$.

The analysis above suggests that if the deviation factor at the reduced value of feedback could be maintained constant over the operating band of the amplifier, there would be a constant, uniform deviation for each setting of the regulator means representing a particular feedback less than infinite feedback. This means that for deviations at one frequency for two values of $|\mu\beta|$ to be in the same ratio as

those at another frequency for two values of $|\mu\beta|$ of the same ratio as the first pair,

$$\frac{|\mu\beta|_1 (\cos \varphi_1 + j \sin \varphi_1)}{1 - |\mu\beta|_1 \cos \varphi_1 - j |\mu\beta|_1 \sin \varphi_1} = \frac{|\mu\beta|_2 (\cos \varphi_2 + j \sin \varphi_2)}{1 - |\mu\beta|_2 \cos \varphi_2 - j |\mu\beta|_2 \sin \varphi_2} \quad (6)$$

where

$$\begin{aligned} |\mu\beta|_1 &\text{ is equal to } |\mu\beta| \text{ at frequency } f_1 \\ |\mu\beta|_2 &\text{ is equal to } |\mu\beta| \text{ at frequency } f_2 \\ \varphi_1 &\text{ is equal to the phase angle of } |\mu\beta|_1 \\ \varphi_2 &\text{ is equal to the phase angle of } |\mu\beta|_2 \end{aligned}$$

which may be reduced to

$$\frac{|\mu\beta|_1}{|\mu\beta|_2} = \frac{\cos \varphi_1}{\cos \varphi_2} \left[\frac{1 - \frac{1}{2|\mu\beta|_1 \cos \varphi_1}}{1 - \frac{1}{2|\mu\beta|_2 \cos \varphi_2}} \right] \quad (7)$$

Since

$$\frac{|\mu\beta|_1}{k|\mu\beta|_1} = \frac{|\mu\beta|_2}{k|\mu\beta|_2} \quad (8)$$

where k is a constant,

$$\frac{k|\mu\beta|_1}{k|\mu\beta|_2} = \frac{\cos \varphi_1}{\cos \varphi_2} \left[\frac{1 - \frac{1}{2|\mu\beta|_1 \cos \varphi_1}}{1 - \frac{1}{2|\mu\beta|_2 \cos \varphi_2}} \right] \quad (9)$$

This relation of Equation 7 may be approximated for $|\mu\beta|_1 \cos \varphi_1$ and $|\mu\beta|_2 \cos \varphi_2$, of the order of 10 or more by neglecting the last fractional ratio. This gives:

$$\frac{|\mu\beta|_1}{|\mu\beta|_2} = \frac{\cos \varphi_1}{\cos \varphi_2} \quad (10)$$

This, of course, means that the $\mu\beta$ -gain or the $\mu\beta$ -phase versus frequency characteristic of the amplifier, or both, must be modified. The $\mu\beta$ -gain characteristic A, shown in Fig. 2, may be retained but the $\mu\beta$ -phase characteristic would have to be modified so as to follow curve B' of Fig. 2. It is simpler to modify both $\mu\beta$ -gain and phase characteristics somewhat to correspond to Relation 10. One such pair of modified $\mu\beta$ -phase and gain characteristics is obtainable for the amplifier of Fig. 1 by replacing the networks 53 and 62 by a network of the type shown in Fig. 4, and by replacing the interstage network 15 by that shown in Fig. 5, i. e., by such change in the network elements as will give the $\mu\beta$ -phase and $\mu\beta$ -gain characteristics that are in accord with the criteria developed herein.

The curves of Fig. 6 show that for the corresponding regulator settings for feedback 0, 10 and 20 decibels below maximum feedback, the gain deviations over the operating range of the amplifier are constant.

What is claimed is:

1. In an amplifying system, an amplifier, a circuit connecting the output and the input of said amplifier for feeding back output energy to said input in such sense as to reduce the gain of the amplifier, and means in said feedback circuit for regulating the magnitude of the feedback energy and thereby the magnitude of the amplifier

gain, the feedback loop gain and the feedback loop phase versus frequency characteristics being such that for a given setting of the regulating means for a finite value of feedback the deviation from the preassigned gain-frequency characteristic of the amplifier for the given setting will be constant with frequency.

2. A negative feedback amplifier in which the amplifier gain is equal to

$$-\frac{1}{\beta} \left(\frac{1}{1 - \frac{1}{\mu\beta}} \right)$$

and in which $\mu\beta$ has some finite value, the feedback loop gain and the feedback loop phase versus frequency characteristics of the amplifier over the frequency range it is desired to amplify being such that, for finite values of feedback loop gain, the expression

$$\left(\frac{1}{1 - \frac{1}{\mu\beta}} \right)$$

is substantially a constant.

3. The method of adjusting for the $\mu\beta$ -effect in a gain-reducing negative feedback amplifier having given maximum feedback loop gain and feedback loop phase versus frequency characteristics, that comprises establishing the feedback loop gain and phase-frequency characteristics so that over the frequency band to be amplified they satisfy the relation

$$\frac{k|\mu\beta|_1}{k|\mu\beta|_2} = \frac{\cos \varphi_1}{\cos \varphi_2} \left[\frac{1 - \frac{1}{2|\mu\beta|_1 \cos \varphi_1}}{1 - \frac{1}{2|\mu\beta|_2 \cos \varphi_2}} \right]$$

where $|\mu\beta|_1$ and $|\mu\beta|_2$ are the feedback loop gains at frequencies f_1 and f_2 , respectively, and φ_1 and φ_2 are the phase angles of $|\mu\beta|_1$ and $|\mu\beta|_2$, respectively, the deviations from the amplifier ideal gain at one frequency f_1 for two values $|\mu\beta|_1$ and $k|\mu\beta|_1$ being in the same ratio as those at the other frequency f_2 for two values $|\mu\beta|_2$ and $k|\mu\beta|_2$ of the same ratio as the first pair, k being a constant.

4. The method of adjusting for the $\mu\beta$ -effect in a gain-reducing negative feedback amplifier having given maximum feedback loop gain and feedback loop phase versus frequency characteristics, that comprises establishing the feedback gain and loop phase-frequency characteristics so that over the frequency band to be amplified they satisfy the approximate relation

$$\frac{\cos \varphi_1}{\cos \varphi_2} = \frac{|\mu\beta|_1}{|\mu\beta|_2}$$

where $|\mu\beta|_1$ and $|\mu\beta|_2$ are the feedback loop gains at frequencies f_1 and f_2 , respectively, and φ_1 and φ_2 are the phase angles of $|\mu\beta|_1$ and $|\mu\beta|_2$, respectively, the deviations from the amplifier ideal gain at one frequency f_1 for two values $|\mu\beta|_1$ and $k|\mu\beta|_1$ being in the same ratio as those at the other frequency f_2 for two values $|\mu\beta|_2$ and $k|\mu\beta|_2$ of the same ratio as the first pair, k being a constant.

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