U.S. Patent 2,102,671 — Harold S. Black

Wave Translation System

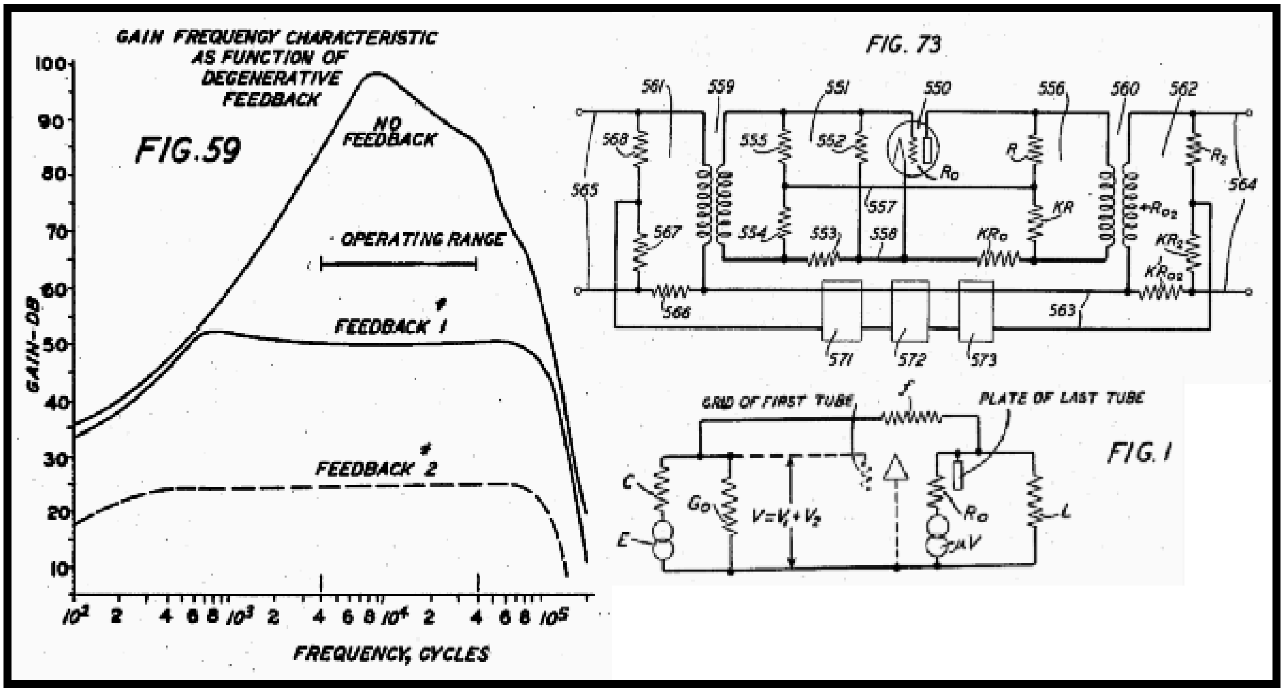
Application filed in 1932 — Patent issued to *Bell Labs* in 1937

Any electrical engineer who has ever designed an amplifier or active filter around an op-amp has made use of the fundamental principle of negative ("degenerative") feedback. Harold Black taught this principle in exhaustive detail in his 1937 patent, taking 35 drawing sheets and 52 pages to tell the story. The patent discusses complex effects of feedback on impedance, gain, stability, and "wave shaping" (filtering).

Fortunately for the analog engineers among us, this fundamental patent and its 126 claims expired in 1954. Now we are free to take advantage of Black's discoveries that "distortion can be reduced in any amplifying system by use of negative feedback," and "the stability of operation of an amplifier can be greatly improved by the use of negative feedback."

The following is the text of claim 20, one of the 113 independent claims of this patent:

> A wave amplifying system having input and output and a feedback path from said output to said input whereby a closed wave propagation path is provided including an amplifier, the wave propagation constant for said closed path having a modulus substantially greater than unity for the frequencies of waves to be amplified by the system.



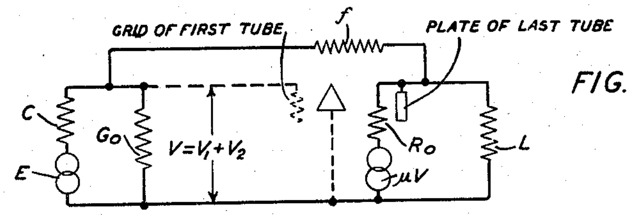
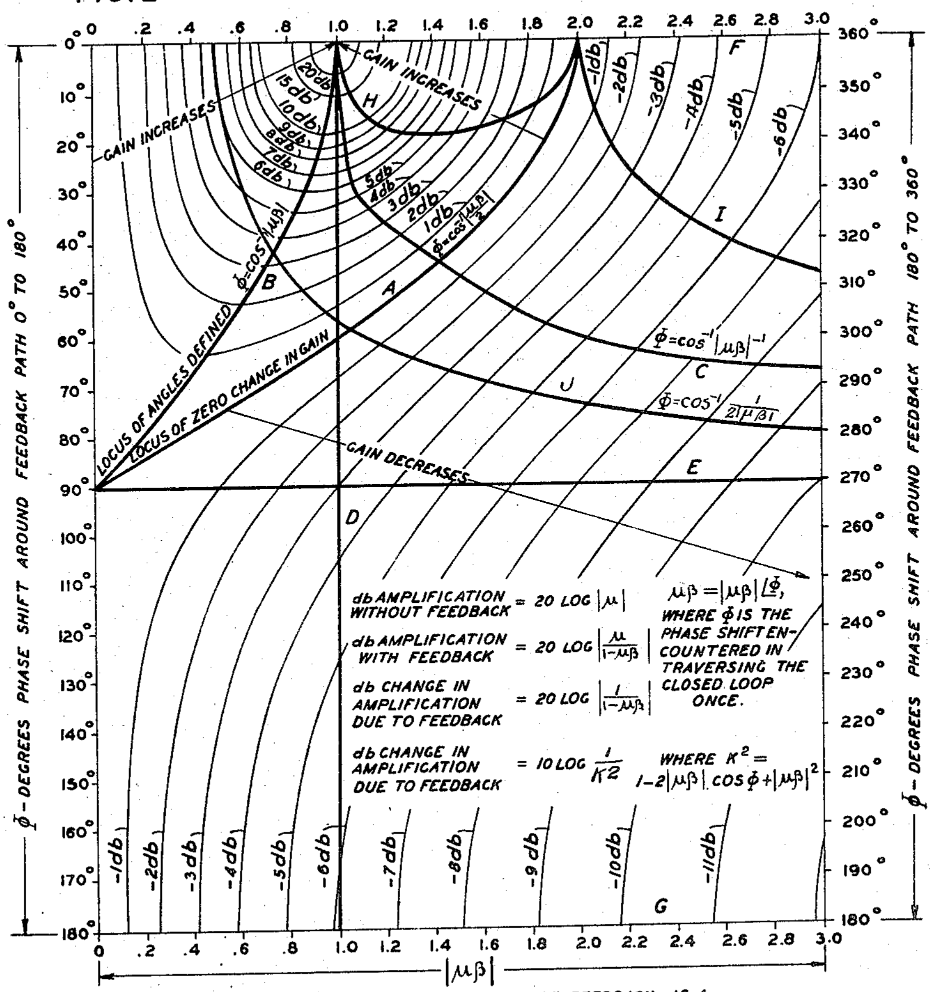


FIG. 1

FIG. 2



μβ, WHICH IS INDICATIVE OF THE AMOUNT OF FEEDBACK, IS A COMPLEX QUANTITY WHICH MAY BE VIEWED AS REPRESENTING THE RATIO BY WHICH THE AMPLIFIER AND FEEDBACK CIRCUIT (OR IN GENERAL μ AND β) MODIFY A VOLTAGE IN A SINGLE TRIP AROUND THE CLOSED PATH.

INVENTOR
H. S. BLACK
BY H. A. Burgess
ATTORNEY

WAVE TRANSLATION SYSTEM

Filed April 22, 1932

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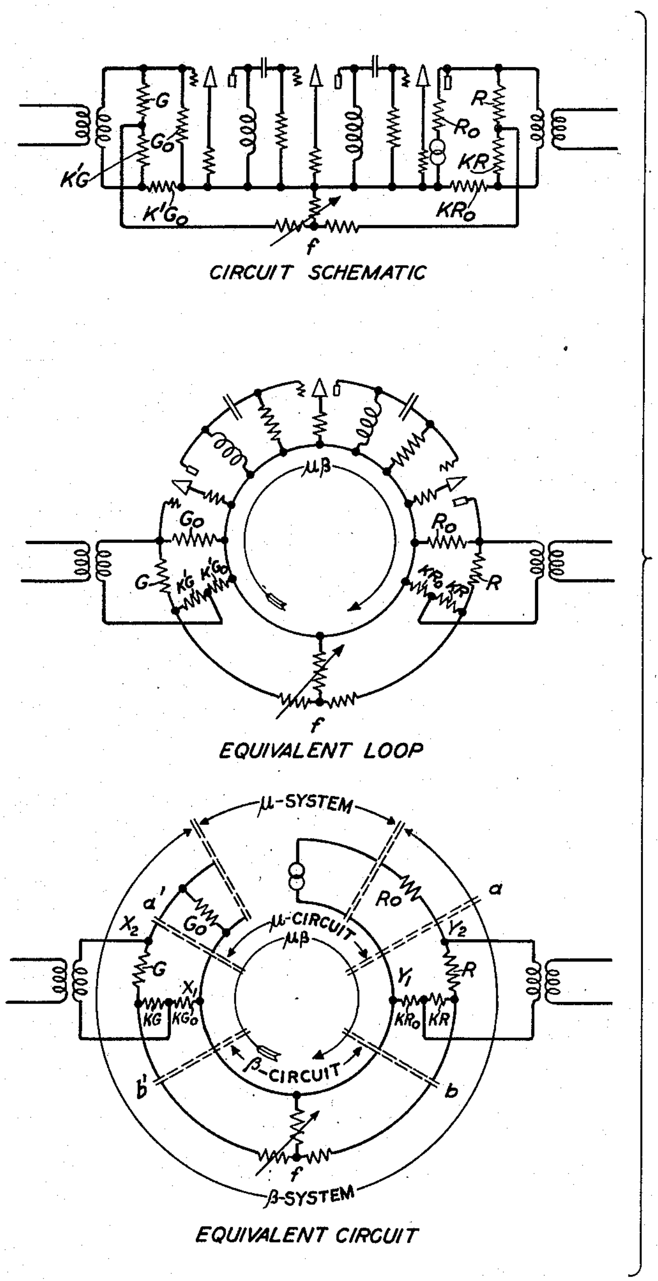

FIG. 18
ILLUSTRATIVE APPLICATION OF METHODS OF FIGS. 14, 15, 16, AND 17

INVENTOR
H. S. BLACK
BY H. A. Burgess
ATTORNEY

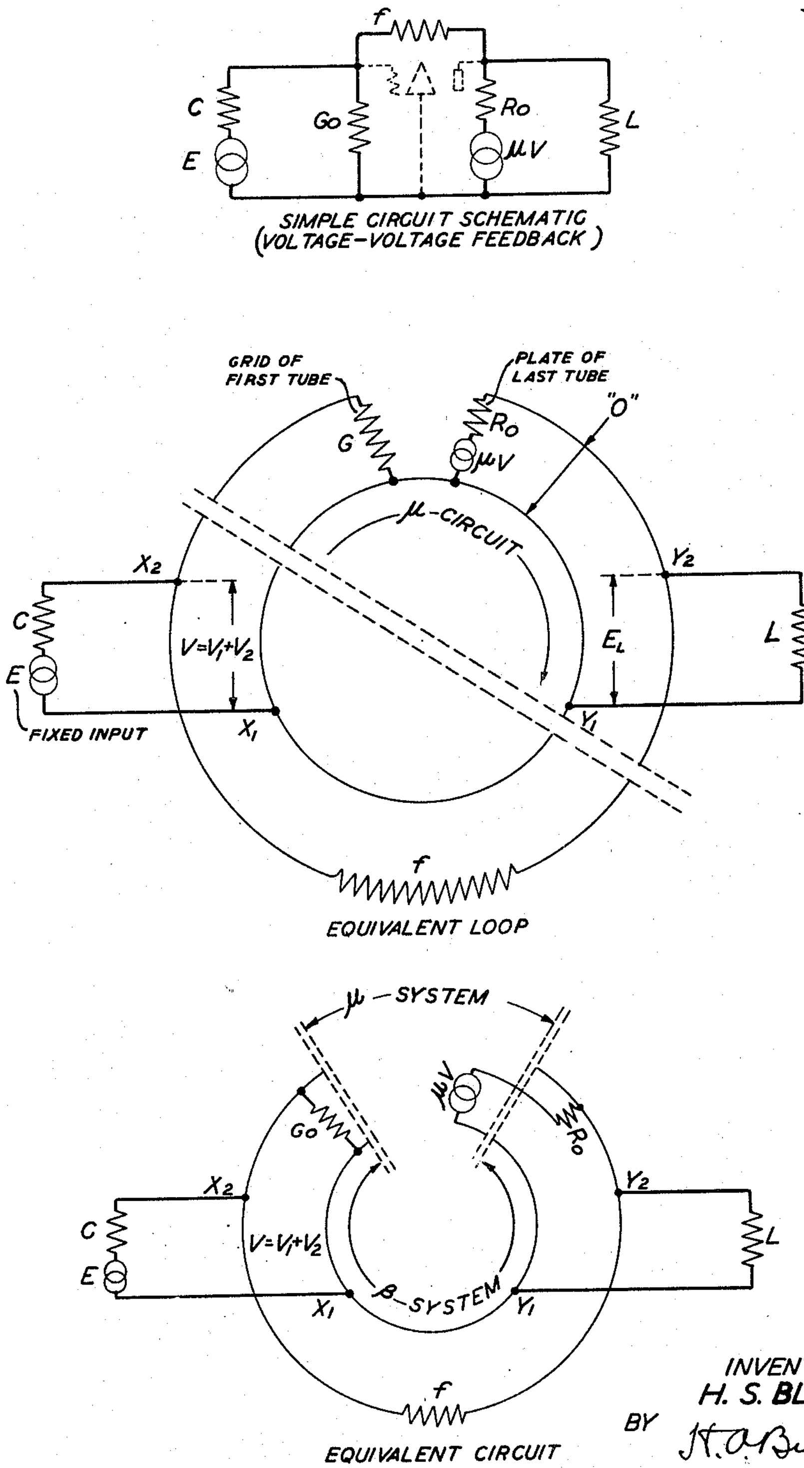

FIG. 19
ILLUSTRATIVE APPLICATION OF METHODS OF FIGS. 14, 15, 16 AND 17

INVENTOR
H. S. BLACK
BY H. A. Burgess
ATTORNEY

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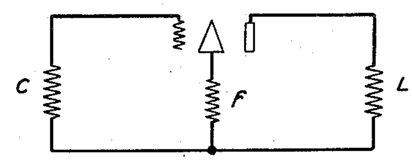
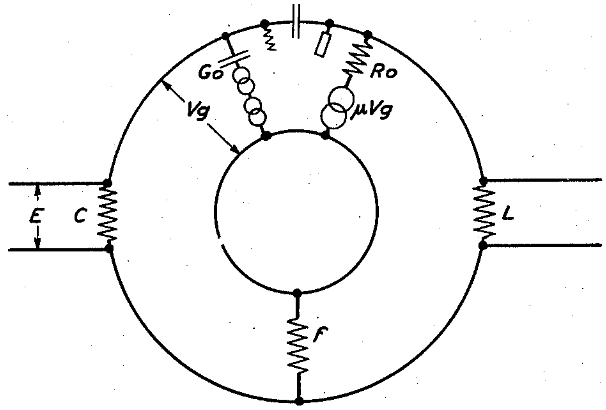
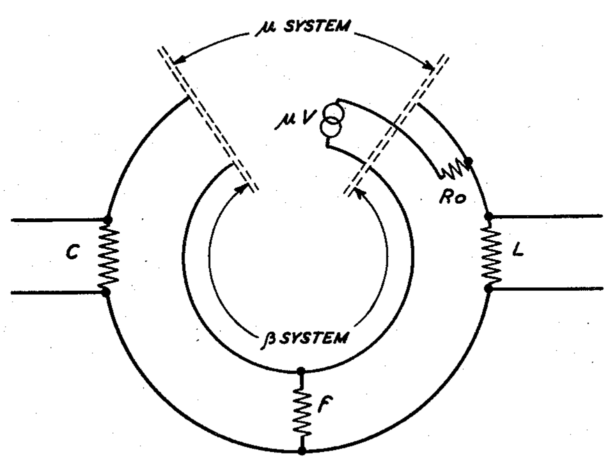


SIMPLE CIRCUIT SCHEMATIC
(COMMON IMPEDANCE FEEDBACK)



EQUIVALENT LOOP



EQUIVALENT CIRCUIT

FIG. 20
ILLUSTRATIVE APPLICATION OF METHODS OF FIGS. 14, 15, 16 AND 17

INVENTOR
H. S. BLACK
BY H. A. Burgess
ATTORNEY

FIG. 37

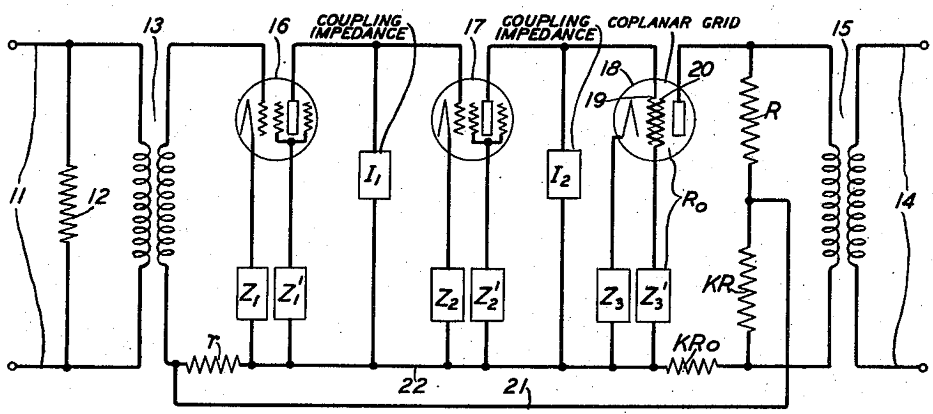
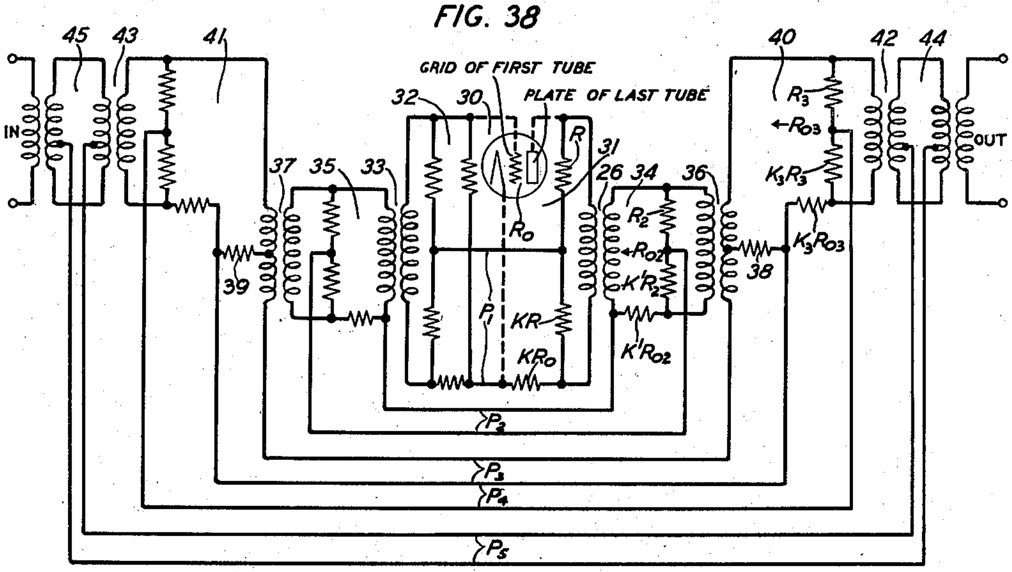


FIG. 38



INVENTOR
H. S. BLACK
BY H. A. Burgess
ATTORNEY

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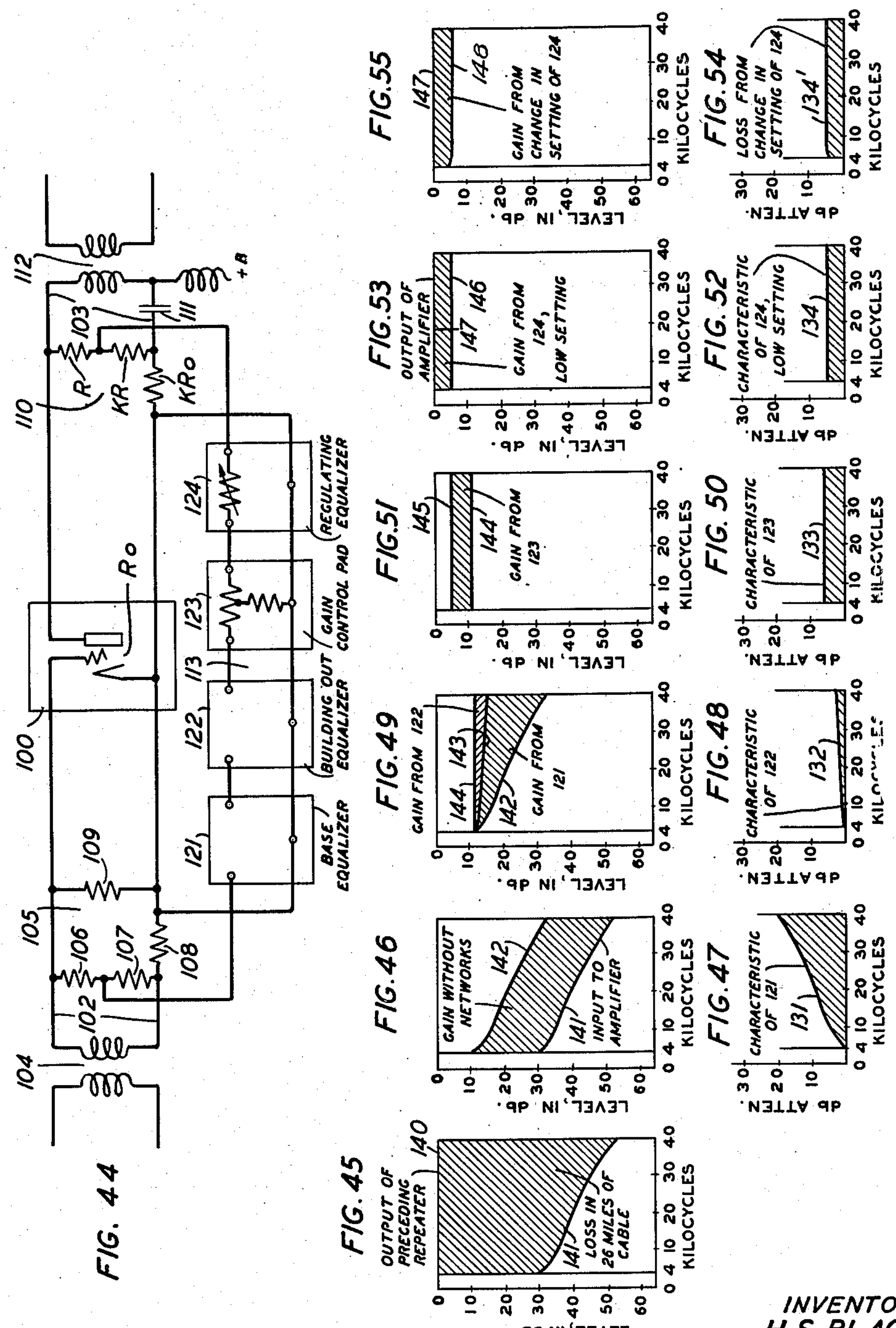

INVENTOR
H. S. BLACK
BY *H. A. Burgess*
ATTORNEY

WAVE TRANSLATION SYSTEM

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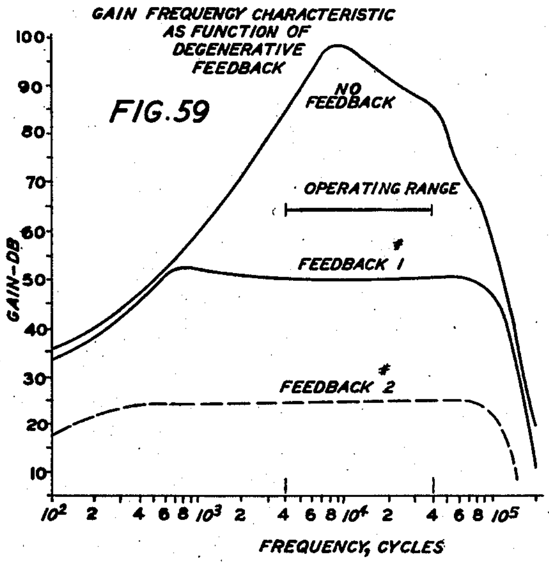

FIG. 59

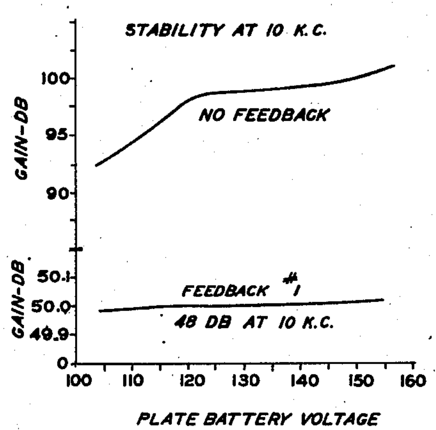

FIG. 60

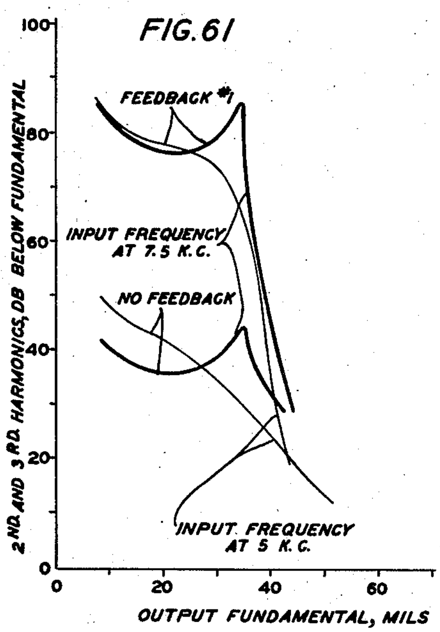

FIG. 61

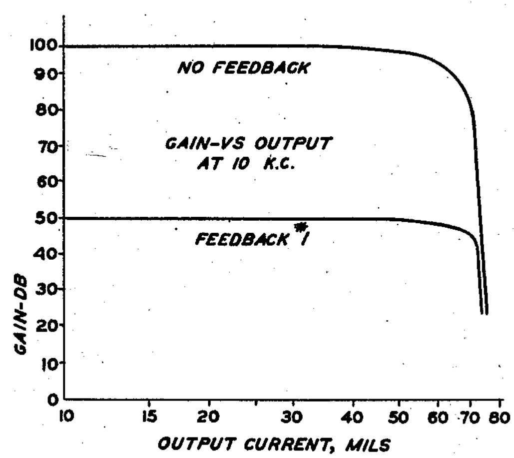

FIG. 62

INVENTOR
H. S. BLACK
BY H. A. Burgess
ATTORNEY

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FIG. 72

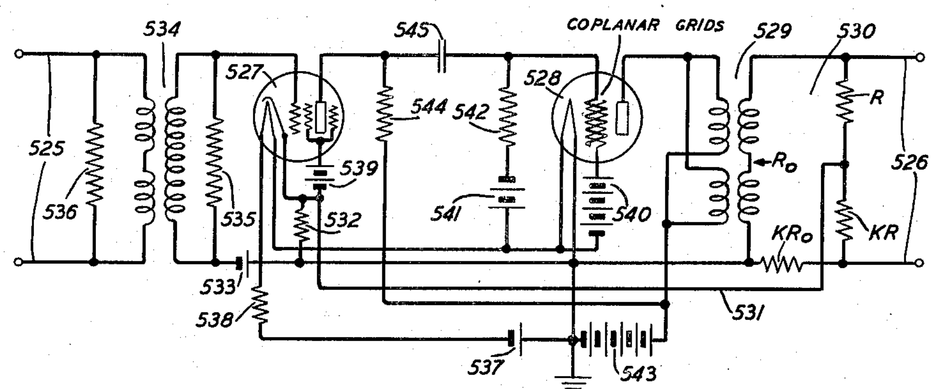
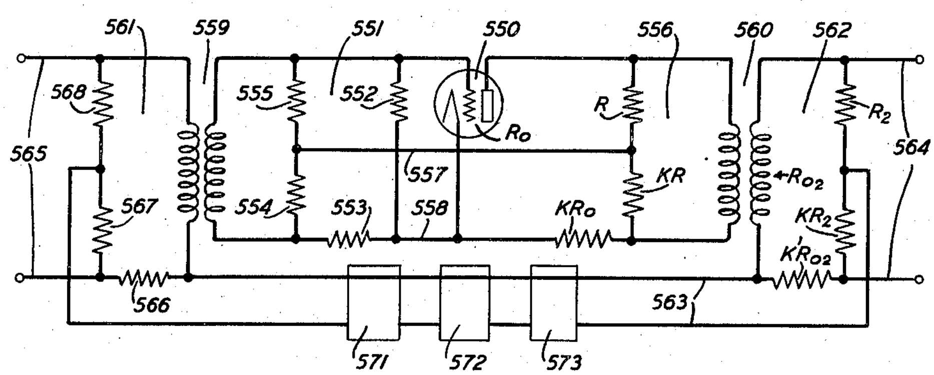


FIG. 73



INVENTOR
H. S. BLACK
BY
H. A. Burgess
ATTORNEY

Patented Dec. 21, 1937 2,102,671

UNITED STATES PATENT OFFICE

2,102,671

WAVE TRANSLATION SYSTEM

Harold S. Black, Westfield, N. J., assignor to Bell Telephone Laboratories, Incorporated, New York, N. Y., a corporation of New York

Application April 22, 1932, Serial No. 606,871
In Canada May 21, 1929

126 Claims. (Cl. 178—44)

This application is in part a continuation of application Serial No. 298,155, filed August 8, 1928, for Wave translation systems and in part a continuation of application Serial No. 439,205, filed March 26, 1930, for Wave translation systems.

The present invention relates to wave transmission apparatus or systems, and more particularly to such apparatus or systems employing an amplifying element provided with a feedback path. The principal field of application of the invention is in apparatus or systems employing negative feedback.

For purposes of simplified introductory discussion and leaving exact definition for a later point, the elements of a system with feedback are: an amplifying element having an input and an output; and a coupling or path for returning some of the output wave to the input of the amplifying element.

The invention is applicable to any kind of wave transmission such as electrical, mechanical or acoustical, and thus far in the description the terms used have been generic to all such systems. The invention will be disclosed herein, however, as specifically applied to electrical systems, it being understood that the principles involved are equally applicable to other types of wave transmission and that the generic claims are intended to include electrical and other than electrical wave systems and apparatus.

Reverting now to the elemental feedback system above described, and taking a typical electrical case, for illustration, the amplifying element may be a grid-controlled discharge tube of ordinary type. The input circuit leads up to the input side from a suitable source of input waves to be amplified, for example, signal waves. The feedback is connected from the output circuit to the input circuit. It will be noted that the waves actually applied to the grid come from two circuit branches, identified as the incoming circuit (from the signal or other wave source) and the feedback circuit. Of course, each of these two waves, the incoming or signal wave and the fed-back wave, could be thought of as being separately applied to the grid, but it will be simpler to think of a summation wave as the voltage actually effective on the grid. Thus, there are three waves to be considered in relation to the input side of the amplifier, (1) the incoming or original wave to be amplified, (2) the fed-back wave, and (3) the voltage wave effective on the grid, this latter being the resultant produced by the algebraic addition of the other two.

The prior art has recognized as generic types, positive feedback and negative feedback. Positive feedbacks have been classified into the so-called regenerative amplifier and the oscillation generator which, from a practical standpoint, are sharply distinguished from each other.

If we picture the fed-back wave and the incoming wave as separately adjustable, we may imagine an increasing amount of fed-back waves in a direction to augment the effect of the incoming wave with a corresponding decrease of the incoming wave. The adjustments may continue until the input wave has been entirely replaced by the fed-back wave. That is, the incoming wave has been reduced to zero and the incoming circuit can be disconnected from the amplifier. The waves in the circuit then become self-sustained and we have the familiar case of the wave generator developing and maintaining continuous oscillations, in a closed loop consisting of the input circuit, the amplifier, the output circuit and the feedback circuit back to the input circuit.

If a smaller amount of positive feedback is employed than is required to produce sustained oscillations, we have the case of the regenerative amplifier. Some of the incoming signal wave after amplification is again put back on the input circuit in such manner as to augment the original incoming signal so that reamplification occurs in the same tube, causing the signal to build up to relatively higher value than could be done by traversing the amplifying element but once. The useful limit of amplification by such a circuit is reached when a further increase in the degree of feedback would result in producing self-oscillation or when the circuit is sufficiently close to the oscillating condition to cause an intolerable amount of signal distortion.

A broad practical distinction between the oscillator and the regenerative amplifier is that in the latter the output current remains under the control of the incoming signal and must follow its variations of starting, stopping, growing stronger or weaker and exhibiting the characteristic quality of the signal, whereas in the oscillator the wave circulating around the regenerative loop is self-determined and is beyond the control of any signal or other input wave.

Turning, now, from positive feedback to negative feedback we find that the principal field of use of negative feedback has been in radio frequency amplifiers.

A radio frequency amplified is a familiar instance of a circuit in which there may exist an inherent tendency toward self-oscillation because of a positive feedback produced by inductive or capacitive coupling between elements of the output and input circuits even where great care in design is exercised to reduce such coupling. These effects become more pronounced as the frequencies become higher and higher. The tendency toward self-oscillation in such circuits places a limit on the amount of amplification that can be used.

Negative feedback has commonly been applied in the prior art in radio frequency amplifiers to oppose the inherent positive feedback. The negative feedback in all such cases has had as its purpose the reduction of the positive feedback. If we imagine that the negative feedback is increased from an infinitesimal amount in any given case, it reaches its optimum value in opposing positive feedback when it just equals the positive feedback. At that point, the net or resultant total feedback is zero and the effect is that of rendering the amplifier a strictly unilateral circuit or one having no feedback, either positive or negative.

In contrast to the negative feedback of the prior art in which, as discussed above, the resultant total feedback is substantially zero, the invention uses negative feedback for an entirely different purpose and in very much larger amounts to achieve improved results in wave translation, e. g., amplification, not envisaged in the prior art.

Applicant has discovered how to use larger amounts of negative feedback than were contemplated by prior art workers with a new and important kind of improvement in tube operation. One improvement is in lowered distortion arising in the amplifier. Another improvement is greater constancy of operation, in particular a more nearly constant gain despite variable factors such as ordinarily would influence the gain. Various other operating characteristics of the circuit are likewise rendered more nearly constant. Applicant has discovered that these improvements are attained in proportion to the sacrifice that is made in amplifier gain, and that by constructing a circuit with excess gain and reducing the gain by negative feedback, any desired degree of linearity between output and input and any desired degree of constancy or stability of operating characteristics can be realized, the limiting factor being in the amount of gain that can be attained rather than any limitation in the method of improvement provided by the invention.

It should be obvious from what has been said that the essential elements of the invention can be embodied in a circuit of quite simple configuration. While, in some elementary forms, the diagram of a circuit incorporating the invention may appear similar to prior art circuit diagrams, this resemblance is superficial since the mode of operation and character of results attained are markedly different from the prior art. The proportioning of the circuit elements must be such as to permit the necessary amounts of amplification and feedback ratios with proper phase relations.

Also, from what has been said, it is apparent that applicant uses negative feedback for a purpose quite different from that of the prior art which was to prevent self-oscillation or "singing". To make this clearer, applicant's invention is not concerned, except in a very secondary way (to be explained later on) with the singing tendency of a circuit. Its primary purpose has no relation to the phenomenon of self-oscillation. If amplifiers could be built exactly like present day amplifiers in all respects except that they were absolutely free of any tendency of self-oscillation regardless of how high their gains might be pushed, it is generally true that there would still be as great need for the present invention. The "perfect" amplifier is one in which the output wave is in all respects an exact replica of the input wave multiplied by some linear factor. The singing tendency is only one of several difficulties encountered in an amplifier. Actually, amplifiers produce distortion components along with the output fundamental components. These modulation or distortion components are mingled with the fundamental wave and detract from its purity. In multiplex carrier systems the distorting effect gives rise to cross-talk and, in any high quality system, it constitutes a limiting factor of design.

Applicant has discovered that distortion can be reduced in any amplifying system by use of negative feedback in accordance with the invention.

Another difficulty in amplifier operation is instability, not used here as meaning the singing tendency but rather signifying constancy of operation as an amplifier with changes in battery voltages, temperature, apparatus changes including changes in tubes, aging and kindred causes. Such instability is a limiting factor where, for example, a large number of repeaters are operated in tandem in a line. A simultaneous tendency toward increased gain by several or all of the repeaters might be disastrous. Without a means of preventing such changes, they become a limiting factor of design.

Applicant has discovered that the stability of operation of an amplifier can be greatly improved by the use of negative feedback.

These two kinds of improvement realizable by use of negative feedback are given by way of example. Other advantages will appear from the fuller description to follow.

The general object of the invention is to employ feedback to improve the operation of a circuit as by decreasing distortion or increasing stability.

The invention, in one aspect, comprises use of enough negative feedback to increase the linearity of an amplifier.

The invention, in one aspect, comprises use of enough negative feedback to improve stability of an amplifier against changes in operating characteristic with changes in constants of component parts of the amplifier circuit or apparatus.

Reverting again to the elemental feedback circuit discussed above, it was pointed out that the prior art used negative feedback to cancel positive feedback giving a resulting circuit with zero feedback. In such cases, the total fed-back wave was made up of some positively fed-back wave and enough negatively fed-back wave to bring the total fed-back wave to zero. Thus, the voltage wave effective on the grid was exactly equal to the incoming wave, nothing being either added to or subtracted from the incoming wave in such case. It was realized that with an increased amount of negative feedback, the voltage wave effective on the grid could be made slightly less than the incoming wave, with consequently lowered gain. Except as this small net negative feedback afforded a margin of safety against self-oscillation it was considered a detriment since it lowered the gain, and there was no realization that, apart from opposing self-oscillation, there was any advantage from the standpoint of amplifier operation in reducing the gain.

Moreover, while various circuits were known involving connections between input and output for suppressing or eliminating some undesired wave component in the system there was no prior realization, as far as applicant is aware, that negative feedback could be used to reduce modulation, improve linearity and increase stability of the circuit for the transmitted waves. Some writers of recognized standing in the field of positive feedback circuits even went so far as to point out that the customary analysis of such circuits led to the conclusion that no greater degree of negative feedback was possible than a degree exactly equal to the positive feedback which corresponded to the singing condition. Such a view precluded any expectation that large amounts of negative feedback could be used in an amplifier for any purpose. According to that view, a limit to the amount of negative feedback would be reached at the point where the voltage effective on the grid is just equal and opposite to the fed-back voltage, for any increase in the fed-back voltage beyond that point would upset the stability of the circuit as an amplifier and make it a generator of oscillations.

Contrary to the teachings of the prior art, applicant utilizes such a large value of negative feedback that it not only may equal but greatly exceed the amplitude of the wave that is effective on the grid. That is, the voltage wave that is effective on the grid is not only smaller than the incoming voltage wave but is smaller than the fed-back voltage wave. In effect, this means that a small wave effective on the grid is controlling a cycle of operations involving waves of much greater magnitude, namely, a larger incoming wave and a larger fed-back wave. Far from resulting in a liability of self-oscillation, applicant has discovered that the greater the negative feedback ratio, the more exact is the correspondence in all respects between the output wave and the incoming wave, so that it may be said that the more complete is the control of the output wave by the incoming wave. The result is greater linearity of amplification and greater constancy of operating characteristics as regards the influence of circuit variables.

In an attempt to gain some physical concept of the action which takes place in the circuit resulting in these improvements, the following elementary picture may be helpful.

It was stated above that the amplified signal wave in the output of an amplifier is accompanied by distortion produced in the tube. An assumption, justified by experience, will now be made that the ratio which this distortion bears to the signal is a function of the amplitude of the output signal, other things being equal. That is, with a given tube and circuit, as the signal output is increased, the percentage of distortion increases. It is further to be noted that a distortion component appearing in the output of an amplifier can be reduced by application to the input circuit of some of the distortion component in reversed phase.

Referring to the simple system with feedback already considered, let it be imagined that a simultaneous control can be made in the amplitudes of the incoming signal and of the fed-back wave such as always to keep the wave effective on the grid at a constant amplitude. Starting out with no fed-back wave, the voltage effective on the grid is that of the incoming signal unmodified by feedback. There is, then, a given amount of output signal and distortion. If, now, negative feedback is gradually introduced in increasing amount and at the same time the incoming signal is increased by an exactly corresponding amount, it is clear that the voltage effective on the grid due to the signal alone remains unchanged, and that, therefore, the signal output remains unchanged in amplitude. By virtue of the negative feedback, however, some of the distortion is being fed back to the grid in such sense as to reduce the distortion appearing in the output. The result is less distortion with no diminution in signal output, a net improvement in linearity of the circuit.

The apparatus for increasing the negatively fed-back wave (e. g., from an infinitesimal or small value) might be visualized as an amplifier of variable gain in the feedback path. Likewise, the apparatus for producing corresponding increase in the signal in the incoming circuit may be thought of as an amplifier of variable gain. Since the coordinated changes assumed to take place in these two amplifiers is a simultaneous increase in their gains by an exactly corresponding amount, the next step in developing the picture is to visualize these two as one and the same amplifier through which both the incoming signal and the fed-back wave are transmitted. This amplifier may be pictured as introduced just ahead of the existing amplifier, that is, between the input to that amplifier and the junction between the incoming circuit and the feedback circuit.

Summarizing the foregoing, it is recalled that an amplifier was first assumed in which there was at the start no feedback, and in which there was a given output of signal and distortion. It was shown that the distortion was reduced relative to the signal by a circuit which is found to differ from the circuit first assumed by the addition of a negative feedback and by an increase in the total gain of the amplifier, still keeping the amplitude of the signal effective on the grid the same as before and consequently the signal output the same. In other words, the gain in the amplifying path was increased but the increase was nullified by a negative feedback.

The foregoing may serve as illustrating in a non-technical and approximate way what is meant by securing greater linearity in an amplifier by providing it with excess gain over that eventually needed and using a negative feedback to cancel the excess gain.

The degree of stability and linearity obtainable is controlled by the feedback, and the feedback can, for example, improve the stability a thousandfold and reduce harmonic currents in the output to one-thousandth and their energy to one-millionth of the values without feedback. (These values are merely illustrative, and not limiting.) Thus the feedback can be highly useful for example, in causing the magnified output to be a faithful reproduction of a signal input. Linearity is essential to such fidelity of reproduction and requires constancy of amplification independent of input amplitude. This implies freedom from harmonic production and other unwanted modulation effects. Stability of transmission is an additional desirable attribute and in certain applications necessary. For example, the stability and linearity afforded by the invention enable large numbers of high gain carrier telephone repeaters (fifty or one hundred, or several hundred, for instance) to be operated in tandem, and thus render multiplex carrier telephony feasible over long circuits of high attenuation, as for example, nonloaded cable circuits one or several thousand miles long.

It is desired to point out that according to the invention and in contrast to prior art methods, the improvement realized in performance, for example in linearity, is not dependent upon a circuit balance of any sort nor upon constancy of balance or of some other relatively critical adjustment or condition, but depends upon the amount of gain reduction.

As shown hereinafter, feedback can be utilized according to this invention to improve the performance of the amplifier or the transducer in other respects also, as for example, with respect to phase shift and phase distortion. (For a discussion of phase distortion, reference may be had to the following publications: "Phase distortion in telephone apparatus"—C. E. Lane, Bell System Technical Journal, July 1930, pages 493–521; "Phase distortion and phase distortion correction" by S. P. Mead in the Bell System Technical Journal, vol. 7, No. 2 for April 1928 at page 195; "Building of sinusoidal currents in long periodically loaded lines" by J. R. Carson, in the Bell System Technical Journal, vol. 3, No. 4, at page 558.)

The feedback path may, in accordance with a feature of the invention, include wave shaping, adjusting or control devices for appropriately affecting the amplifier characteristic or performance. Thus, in addition to its primary function of feeding back a portion of the output waves in gain-reducing phase, it may feed back variable amounts of the output or components of different frequency in different degree or may change the phase or otherwise affect the properties or characteristics of the fed-back waves. As one example, the feedback path of a line repeater may contain a network of equivalent attenuation-versus-frequency characteristic to that of the line, to shape the repeater characteristic so as to compensate line distortion. This and other types of apparatus in the feedback path are disclosed.

The method of controlling the transmission characteristic of the amplifier by the transmission control networks in the feedback circuit is highly advantageous with respect to noise reduction. When the amplifier gain is reduced at any frequency by the feedback circuit, noise originating in either the forwardly transmitting path or the feedback path of the amplifier has its amplitude at the point of origin also reduced, at that frequency. Thus, for example, tube noises originating in any of the tubes of the amplifier (for instance, noises from Schottky effect or from microphonic action), noises from fluctuations of the voltages for energizing the tubes of the amplifiers, and resistance noise (thermal agitation) originating in the transmission control networks of the feedback path or in any other portion of the amplifier are reduced. Consequently, even at low gains, the signal-to-noise ratio in the load circuit is not in any way reduced.

The ability of the invention to improve the linearity and stability of an amplifier by use of negative feedback is of great economic as well as technical importance. The attainment of high power and high quality together in an amplifier has always been an object of especial desire since the power stage or stages in an amplifier are the most expensive to construct and operate. To make tubes in such stages larger so that a given output would represent a smaller load in comparison to their load capacity has been a costly expedient from both standpoints. The invention improves the characteristic of the power stage by adding gain at a lower power part of the amplifier, for example at the input, which can be done relatively cheaply, and by adding a negative feedback as already explained. Thus the same power stage can be operated with greatly improved characteristic or a much smaller power stage can be operated with equivalent quality of output.

Other objects and aspects of the invention will be apparent from the following description and claims.

In the drawings, Figs. 1, 5, 6, 7 and 8 are schematic diagrams of vacuum tube amplifier circuits used in explaining the invention;

Figs. 2, 3 and 4 are curves or plots for facilitating explanation of the invention, Fig. 3 being in the nature of an extension of Fig. 2, and Fig. 4 being a polar plot of functions plotted with rectilinear coordinates in Figs. 2 and 3;

Figs. 9, 10 and 11 are curves, and Figs. 12 and 13 vector diagrams, for facilitating explanation of the invention;

Figs. 14, 15 and 16 are symbolic representations of a simple feedback system for facilitating explanation of the invention; Fig. 17 shows an equivalent circuit of a simple feedback amplifier, illustrating application of principles explained by reference to Figs. 14 to 16; and Figs. 18, 19 and 20 illustrate application of methods of analysis explained by reference to Figs. 14 to 17;

Figs. 21, 22 and 24 are schematic circuit diagrams used in explaining the invention, especially with reference to control of modulation or distortion; and Fig. 23 is a vector diagram facilitating explanation of the invention, especially with relation to such control;

Figs. 25, 26, 27, 28, 29, and also Figs. 30, 31, 31A, 32, 32A, 33, 33A, and 34 are schematic circuit diagrams or equivalent circuits of vacuum tube amplifiers, used in explaining the invention, especially with reference to control of impedance in feedback systems;

Figs. 35A to 35E and 36A to 36H are schematic representations of various methods of feedback or configurations of feedback systems;

Fig. 37 is a diagrammatic showing of an amplifier circuit illustrative of multiple feedback in accordance with the invention;

Fig. 38 is a diagrammatic showing of an amplifier circuit illustrative of repetitions of the feedback process, in accordance with the invention;

Fig. 39 is a diagrammatic showing of a feedback amplifier circuit employing parallel transmission control networks in a feedback path;

Fig. 40 is a diagrammatic showing of a circuit illustrative of stabilization of a transmission loss by feedback, in accordance with the invention;

Figs. 41 and 42 are circuit diagrams for facilitating explanation of certain aspects of the invention; Fig. 43 shows a feedback amplifier embodying one form of the invention; Figs. 43A, 43B and 43C are diagrams, and Fig. 43D a set of curves for facilitating explanation of the operation of the amplifier of Fig. 43; and Fig. 43E shows a modification of the amplifier of Fig. 43;

Fig. 44 is a schematic diagram of a negative feedback amplifier embodying a form of the invention; Figs. 45 to 55 show curves facilitating