

March 17, 1936.

L. A. WARE

2,033,963

WAVE TRANSLATING SYSTEM

Filed Dec. 21, 1933

FIG. 1

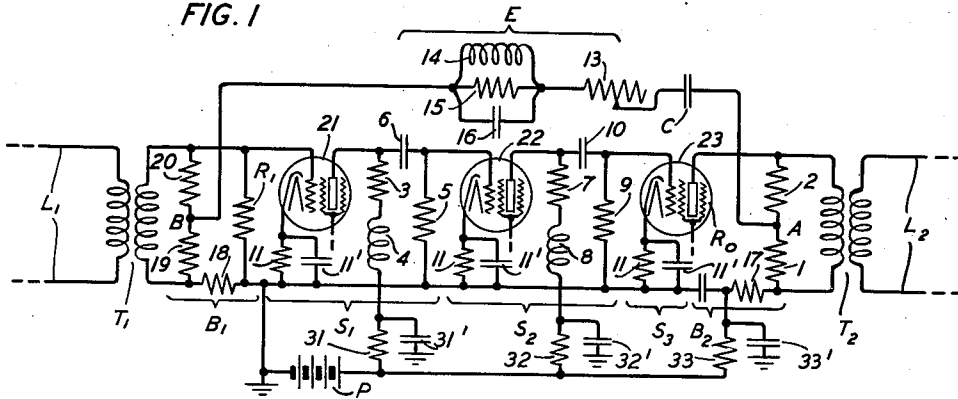


FIG. 2

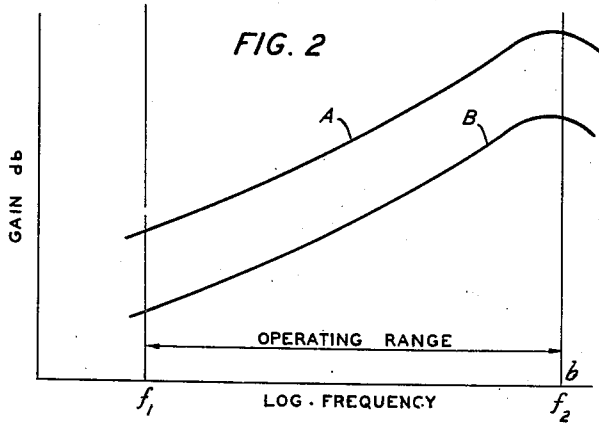
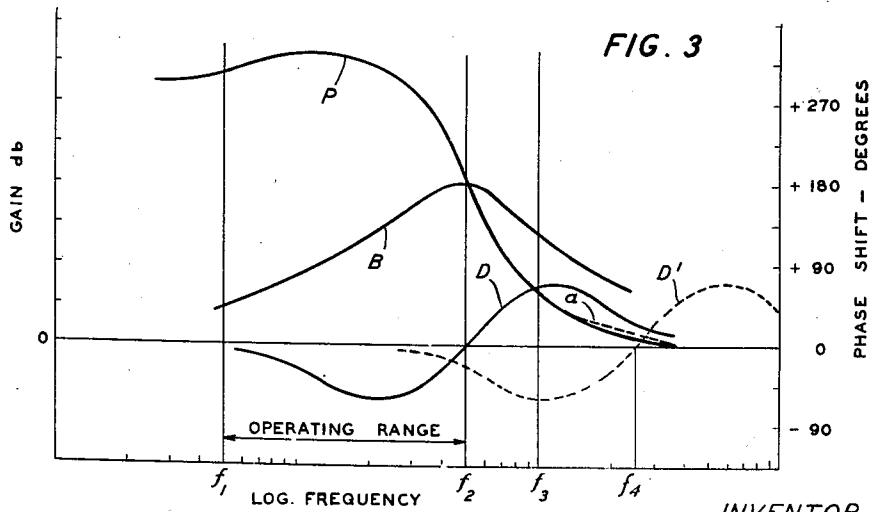


FIG. 3



INVENTOR
L. A. WARE

BY

H. A. Burgess

AT TORNEY

UNITED STATES PATENT OFFICE

2,033,963

WAVE TRANSLATING SYSTEM

Lawrence A. Ware, East Orange, N. J., assignor
to Bell Telephone Laboratories, Incorporated,
New York, N. Y., a corporation of New York

Application December 21, 1933, Serial No. 703,425

8 Claims. (Cl. 178-44)

This invention relates to wave translation and especially to retroaction or feedback in wave translating systems, as for example in electric wave amplifying systems.

An object of the invention is to control transmission properties of such systems, as for example to control variation, with frequency, of amplifier gain, gain stability and modulation or distortion.

It is also an object of the invention to obtain high and stable amplifier gain in such systems with low modulation or distortion.

Further objects of the invention are to control amplitude and phase of waves in such systems, and especially to control singing tendency of such systems.

Certain terms and symbols used herein have the following significance. Singing refers to operation such that an impressed small disturbance which itself dies out results in a response that does not die out but goes on indefinitely, either staying at a relatively small value or increasing until it is limited by the non-linearity of the system. The amplification of a vacuum tube amplifier without feedback is designated μ and is the complex quantity by which the voltage on the grid of the first tube must be multiplied to obtain the phase and magnitude of the total resulting voltage in the plate circuit of the last tube. Amplification ratio is the absolute or scalar value of μ . Gain is twenty times the logarithm of the amplification ratio. The quantity $\mu\beta$ represents the propagation once around the closed feedback loop of a feedback amplifier. It follows that β designates the complex quantity by which a driving voltage in the space path of the last tube, in series with the plate-filament impedance in that tube, must be multiplied to give the voltage that it—the driving voltage alone—acting through the feedback path, will produce on the grid of the first tube. As shown in a copending application of H. S. Black, Serial No. 606,871, filed April 22, 1932, for Wave translation systems, the amplification of a feedback amplifier is

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

and the corresponding change in amplification caused by the feedback action is

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

The quantity

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

is a quantitative measure of the amount of feedback, and herein, as in that application, the feedback is described as positive feedback or nega-

tive feedback according as the absolute value of

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

is greater or less than unity.

In one specific aspect the invention is embodied in vacuum tube amplifiers of a general type disclosed in the above mentioned copending application and in British Patent 371,887. In that type, waves, including those of the range of transmitted frequencies, are so fed back from the output to the input as to reduce the gain of the amplifier below the value that it would have without feedback in order to reduce unwanted modulation or non-linear effects and render the gain stability greater than it would be without feedback; and, moreover, the feedback path is given transmission characteristics that yield desired amplifier characteristics, for example, an amplifier gain-frequency characteristic that equalizes attenuation of the circuit in which the amplifier is connected or compensates for variation of the circuit attenuation with frequency over the utilized frequency range.

In such amplifiers, where tube modulation reduction for modulation components of given frequencies is to be large, it is proportional to the gain (for those modulation components) in a single trip around the closed feedback loop and consequently that gain should be large. The modulation components that it is desired to reduce by feedback are usually waves of frequencies within the utilized frequency range, e. g. within the range of the frequencies of the signal waves to be amplified by the amplifier. Therefore, it is usually desirable to have the loop gain (i. e. the decibel gain for a single trip around the loop) large for the frequencies of the utilized range. Moreover, this large loop gain is also desirable as giving large increase of gain stability by the feedback. Further, with the loop gain large, the amplifier gain is approximately equal to the loss in the feedback path (since then $\mu\beta \gg 1$, and

$$\frac{\mu}{1-\mu\beta} = -\frac{\mu}{\mu\beta} = -\frac{1}{\beta};$$

and then the required amplifier gain-frequency characteristic can be obtained by giving the feedback path a corresponding loss-frequency characteristic; and consequently the amplifier can be made to equalize line attenuation by making the loss-frequency characteristic of the feedback path like that of the line over the utilized frequency range, or can be made to compensate to any desired degree for variation of line attenuation with frequency, by making the variation of the loss in the feedback path, with frequency, the same as the amplifier gain-frequency variation required for the desired degree of line attenuation equalization.

So long as the loop gain is large, the gain of the amplifier without feedback is of no importance in determining the desired gain of the amplifier with feedback. However, the distortion reduction produced by feedback is approximately equal to the gain reduction produced by the feedback, so the gain without feedback must, at each utilized frequency, exceed the desired value of gain with feedback, at that frequency, by the amount of gain reduction that the feedback produces at that frequency or the amount of distortion reduction that it is desired to have the feedback produce at that frequency; and, especially when the amplifier distortion reduction by feedback is to be large and the amplifier gain (with feedback) is to be high and is to be made variable in a given manner with frequency (for example by connecting a line attenuation equalizing network in the feedback path), the obtaining, throughout the utilized frequency range and particularly at the frequency of maximum line attenuation and maximum amplifier gain with feedback, of sufficient amplifier gain with sufficient amplifier distortion reduction by feedback, can be facilitated by having the feedback produce only the required amount of gain reduction and distortion reduction at the various frequencies of the utilized range, (and therefore having the gain without feedback and the distortion reduction by feedback not unnecessarily large at the frequencies of relatively low line attenuation and relatively low gain with feedback). In many cases it is satisfactory or desirable to have the amount of modulation reduction that feedback produces approximately equal for all utilized frequencies. For example, the desired characteristic of output power versus frequency depends upon various considerations (such as line attenuation, interference from extraneous sources, resistance noise from the line, resistance and other noise generated in the amplifier, modulation, and any noise and modulation reduction obtained by feedback in the amplifier), and in many instances may be approximately flat, with the amplitude of the modulation that falls in the various channels approximately the same for all of the channels, so that if the modulation reduction (resulting from feedback) be made the same for all channels the modulation reduction will be proportional to the modulation. Consequently, in many cases it is desirable to have approximate parallelism of the gain-frequency characteristic of the amplifier with feedback and the characteristic of the amplifier without feedback, this parallelism facilitating obtaining, throughout the operating frequency range, sufficiently high gain with sufficiently low distortion.

In its specific aspect mentioned above, the invention is a negative feedback amplifier having in its feedback path a line attenuation equalizer whose loss-frequency characteristic is approximately parallel to the gain-frequency characteristic of the amplifier without feedback. For example, the amplifier may have interstage coupling circuits that are shunt resonant circuits tuned to the top operating frequency of the amplifier and rendering the gain-frequency characteristic of the amplifier without feedback approximately parallel to the gain-frequency characteristic of the amplifier with feedback.

In practice, when the loop gain is large for the frequencies of the utilized frequency range, it is greater than zero for some higher frequency and for some lower frequency and if the loop phase shift (i. e. the phase shift experienced by waves in passing once around the loop) is zero or a

multiple of 360° for any frequency at which the loop gain equals or exceeds zero decibels, the amplifier may sing at that frequency. (As indicated in the above mentioned copending application, a criterion for freedom from singing is given by Nyquist's rule in his article on "Regeneration Theory", Bell System Technical Journal, January, 1932, pages 126 to 147. Such criterion is also given in H. Nyquist Patent No. 1,915,440, June 27, 1933.) To avoid the singing condition (as well as for other reasons), it is desirable to control the loop phase shift and the loop gain carefully with respect to the entire frequency spectrum. If the value of the loop phase shift were maintained at $\pm 180^\circ$ it would be as remote as possible from the potential singing values of 0° and multiples of 360° ; however, in practice it is not necessary to attain this condition. The requirement for freedom from singing will always be met if for every frequency of loop gain, (i. e., every frequency at which the loop gain is zero or greater) the loop phase shift differs from zero and every multiple of 360° , or in other words if the loop phase shift frequency characteristic does not cross or touch the zero phase shift axis in the frequency range of loop gain. (It is not to be inferred that this requirement is always essential for freedom from singing. A criterion for such freedom is given by Nyquist's rule, as referred to above.)

In designing an amplifier with negative feedback for distortion reduction, assuming the vacuum tube or tubes of each stage in the loop to introduce a phase shift having a constant component of 180° (in addition to any component due to inter-electrode capacitance, for example), the number of vacuum tube stages used in the loop may be made either odd or even, to facilitate control of singing tendency. The question whether an odd or an even number is more suitable will depend upon whether the loop is made to have phase reversing means other than the tubes, and upon what other phase shifts are present in the loop. If, over the frequency range of loop gain the constant component of the total loop phase shift is any odd multiple of 180° , then it is necessary that the total variation of the loop phase shift with frequency over that frequency range be maintained within limits of $+180^\circ$ and -180° in order to make the total loop phase shift differ from zero and every multiple of 360° for every frequency in that frequency range.

The difficulty of insuring that the variation of loop phase shift with frequency is maintained within the required limits over the frequency range of loop gain is in general increased by the fact that, (as brought out, for example, in the above mentioned copending application), when the distortion reduction and associated amplifier gain reduction produced by feedback action is to be large, the gain of the amplifier without feedback must then correspondingly exceed the gain required with feedback; because when the gain without feedback, required to produce the desired amount of distortion reducing feedback and the desired amount of gain with feedback, necessitates use of a plurality of stages and a plurality of interstage coupling circuits, the variation of the phase shift around the closed loop with frequency may become large at low frequencies or high frequencies or both, especially at frequencies above or below the operating frequency range. Moreover, the difficulty is often greatly increased by the presence of a line attenuation equalizer in the feedback path, for example the equalizer phase shift passing through zero at the critical

frequency or frequency of maximum attenuation of the equalizer, for instance in the neighborhood of the top operating frequency, and having at a given frequency below and in the neighborhood of its critical frequency, phase shift equal and opposite to the remainder of the loop phase shift at a second given frequency in the neighborhood of the first given frequency, with the consequence that singing may result if any two such frequencies of equal and opposite phase shift are allowed to be equal.

In its specific aspects mentioned above, the invention is a negative feedback amplifier with a line attenuation equalizer in its feedback path, the loop phase shift without the equalizer falling rapidly from high positive values to low positive values with increase of frequency in the neighborhood of the top operating frequency, and the equalizer phase shift changing from substantial positive values to substantial negative values with decrease of frequency in the neighborhood of the top operating frequency, the frequency at which the equalizer phase shift changes sign being so low that at each frequency at which the equalizer phase shift is negative the remainder of the loop phase shift is positive and greater in absolute magnitude.

In the case of the amplifier referred to above in which the gain-frequency characteristic of the amplifier without feedback is approximately parallel to the characteristic with feedback, the loop gain at low frequencies is less than if the amplifier gain without feedback were as high for the low frequencies of the operating range as for the high frequencies; and this low loop gain is favorable for avoiding singing tendency at frequencies below the operating range.

As indicated above, amplifier gain and modulation, and loop phase shift, present important requirements in operation of feedback amplifiers, especially in operation of high frequency wide band, negative feedback amplifiers employing feedback action for equalizing line attenuation and reducing modulation or distortion.

Objects of the invention are to control such gain and modulation and such phase shift.

It is also an object of the invention to obtain high gain with low distortion, over the operating frequency range, while equalizing line attenuation by negative feedback without producing singing.

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

In the accompanying drawing:

Fig. 1 is a circuit diagram of an amplifier embodying the specific aspects of the invention that are referred to above; and

Figs. 2 and 3 show curves facilitating explanation of the invention.

In Fig. 1 a negative feedback amplifier amplifies waves received by input transformer T_1 from line or circuit L_1 and transmits the amplified waves through output transformer T_2 to line or circuit L_2 . The amplifier shown by way of example comprises a forwardly transmitting path including three vacuum tube stages S_1 , S_2 and S_3 in tandem, and comprises a feedback path from A to B, including a stopping condenser C for preventing passage of direct current and an equalizer E for equalizing the line attenuation to any desired degree. The stages S_1 , S_2 and S_3 comprise screen grid heater type vacuum tubes 21, 22 and 23, respectively, each of high mutual conductance and low interelectrode capacities,

especially the capacity between the plate and the control grid. The equalizer E comprises a resonant circuit made up of parallel connected inductance 14, resistance 15 and capacitance 16 connected in the feedback path in series with an adjustable attenuating resistance 13 which is variable for varying the amplifier gain. An amplifier input bridge network B_1 renders the feedback path and the circuit L_1 conjugate and an amplifier output bridge B_2 renders the feedback path and the circuit L_2 conjugate, in the manner disclosed, for example, in the above mentioned copending application and in the above mentioned British patent. The ratio arms of bridge B_2 are resistances R_0 , 17, 1 and 2. The ratio arms of bridge B_1 are resistances R_1 , 18, 19 and 20.

The amplifier is of the general type (referred to above as disclosed in the copending application 606,871 and in the British Patent 371,887) in which, over the operating frequency range, loop gain is much greater than unity, and in which waves, including fundamental and distortion waves of the operating frequency range, are so fed back as to reduce the amplifier gain below its value for operation without feedback, in order to reduce distortion correspondingly and render the gain stability greater than for operation without feedback.

The circuits for supplying heating current to the filaments and operating potentials to the screen grids of the amplifier are not shown, as they can readily be supplied by those skilled in the art.

A battery P is shown as supplying plate potential for all of the tubes, resistor 31 and bypass condenser 31' preventing transmission of variations between the battery and tube 21, resistor 32 and condenser 32' functioning similarly for tube 22, and resistor 33 and condenser 33' functioning similarly for tube 23.

A network individual to each tube, consisting of a resistor 11 and a small condenser 11' connected in parallel in the cathode lead of the tube, common to the grid and plate circuits of the tube, supplies negative biasing potential for the grid of the tube and moreover, as indicated hereinafter, provides negative feedback local to the tube for controlling the loop phase shift of the amplifier to reduce tendency of the amplifier to sing around the feedback loop (including equalizer E) at frequencies above the utilized range.

The interstage circuit coupling tubes 21 and 22 includes a plate circuit resistor 3 and inductance 4 in series, a grid leak resistor 5 and a stopping condenser 6, and similarly the coupling for tubes 22 and 23 includes a plate circuit resistor 7 and inductance 8, a grid leak resistor 9 and a stopping condenser 10, the elements of these interstage coupling circuits being proportioned to give the amplifier without feedback, or the forwardly transmitting portion of the amplifier, the desired gain and gain-frequency characteristic, as described hereinafter.

The amplifier is suitable for transmission of waves of a wide band of frequencies extending up to high frequencies with high gain and gain stability and low modulation, being suitable for instance for such transmission in long distance communication at frequencies extending for example over a range from 50 to 500 kilocycles, important contributions to such suitability being made by the specially adjusted interstage networks coupling the tubes of high mutual conductance and by the negative feedback giving the desired degree of line attenuation equalization

yet cooperating with the interstage coupling to give the required amplifier gain stabilization and modulation reduction over the utilized frequency range.

- 5 In carrier telephony, for example, a large number of communication channels on a single conductor pair is desirable for economic reasons. This involves high frequencies and consequently high line attenuation. It, therefore, requires
10 many repeaters with close spacing and with high gain per amplifier, and moreover makes close spacing of channels in the frequency spectrum advisable. This all leads to difficulties as regards modulation and gain stability; and to reduce these difficulties by the negative feedback
15 type of amplifier in which gain is exchanged for improvement in modulation and in gain stability, requires that the gain of the amplifier without feedback be correspondingly great, at high frequencies. Moreover, as indicated above, the difficulty of obtaining the required gain is increased by the fact that if a large number of stages were used in the amplifier the difficulty of preventing the phase shift around the feedback loop from
20 causing singing would be increased.

- To obtain the required high gain (with feedback) and low modulation, over a wide frequency range extending up to high frequencies, the vacuum tubes of the amplifier should have high mutual conductance and the vacuum tube coupling
30 circuits should have high impedance over the operating frequency range, and the phase shift in the feedback circuit should be made low, as excessive phase shift might cause singing, especially at high frequencies. Moreover, the input and output transformers should be given high gain or high voltage step-up with low loss over the operating frequency range.

- A practical condition for facilitating successful operation is that the phase shift of the entire circuit be kept as low as practicable. The use of high mutual conductance tubes with high plate impedances makes it desirable to use a coupling circuit which is tuned to the highest frequency in
45 the operating range, where the line attenuation is highest. These couplings, which are shown as of the impedance type, are adjusted to produce a gain-frequency curve (for the amplifier without feedback) which is substantially parallel to the
50 line attenuation-frequency curve. Gain-frequency characteristics of the amplifier without feedback and with feedback are given by curves A and B, respectively, in Fig. 2. The feedback circuit is of low impedance, the equalizer being
55 of a low impedance type with a characteristic that causes the feedback circuit attenuation-frequency curve, and therefore the gain-frequency curve for the amplifier with feedback, to be parallel with the cable attenuation-frequency curve.
60 Since the gain of the amplifier circuit is dependent primarily upon the feedback circuit attenuation and the input and output transformers for the amplifier, the gain can be adjusted by the feedback equalizer alone.

- 65 In the operation of the amplifier, the feedback connection between resistances 1 and 2 taps off a certain portion of the output of stage S_3 according to the adjustment of the resistances of bridge B_2 and feeds it back through the equalizer
70 E to the input bridge, where the feedback voltage and the input signal are combined. In the complete circuit from A to B to A, it is desirable to provide the following conditions: an adjustment of the interstage couplings which will produce the highest gain of the amplifier (without

feedback) at the frequency of highest line attenuation; a characteristic of equalizer E which will produce a gain-frequency characteristic for the amplifier with feedback that is parallel to the gain-frequency characteristic of the amplifier without feedback; and a total phase shift in the elements, exclusive of the 180° reversal in the tubes, of less than 180° , over the entire frequency range of loop gain, i. e., over the entire frequency range in which the voltage step-up around the circuit from A to B to A is greater than unity.

As the frequency increases from a value far below the operating frequency range to a value far above that range the phase shift of the interstage couplings changes from positive 90° each to negative 90° each, passing through zero value at a frequency dependent upon the adjustment of the circuit elements 3, 4, 5, 6, 7, 8, 9 and 10. The operation of the interstage couplings depends upon the resonating of the inductances 4 and 8 with the effective interstage circuit capacities. This adjustment is made in such a manner that the peak of the interstage impedance, and zero phase shift, occur substantially at the frequency of highest line attenuation, as indicated in Fig. 3 wherein curve B is the gain-frequency characteristic of the amplifier with feedback and curve P is the phase-shift frequency characteristic of the forwardly transmitting portion of the amplifier, comprising stages S_1 , S_2 and S_3 . In order to prevent the combined phase shifts of the interstage circuits from approaching 180° too rapidly on either side of the maximum-gain frequency, or in order to prevent the curve P from approaching zero degrees or 360° too rapidly above or below the frequency of maximum gain, the resistance values of grid leaks 5 and 9 are made as low as possible without materially affecting the gain. Also the resistances 3 and 7 are adjusted to produce both the right shape of the curve A in Fig. 2 and the correct frequency value of the peak of curve A. The small capacitances 11' shunted across the cathode resistances 11 produce in the interstage coupling a small corrective phase shift at high frequencies, such as at a on curve P in Fig. 3, at a slight expense of gain.

The amplifier, exclusive of the feedback circuit, produces a gain according to curve A of Fig. 2, and has a phase shift greater than 180° below the frequency corresponding to b in Fig. 2 and a phase shift less than 180° above b . The attenuation of the circuit from A to B is a maximum at b , a condition which can be obtained by tuning the resonant circuit made up of elements 14, 15 and 16 to the frequency desired. The height and shape of curve B of Fig. 2, within certain limits, can be adjusted by resistances 13 and 15. The circuit E has the further property that it produces a negative phase shift below and a positive phase shift above the resonant frequency and thus is corrective of the interstage coupling circuits, the phase shift-frequency characteristic of the circuit E being given by curve D of Fig. 3. The feedback circuit is operated with as low values of resistances 1, 17, 18 and 19 as practicable in order to further decrease the effect of shunt capacitances in the feedback circuit which produce detrimental phase shift. This means that resistance 13 should be as low as practicable. If the critical frequency of the equalizer were raised from frequency f_2 to frequency f_4 in Fig. 3, as indicated by the dotted curve D', the resultant (not shown) of curves P and D' would reach zero degrees at a frequency in the neighborhood of

frequency f_3 , and if there were a loop gain at the frequency of zero phase shift the amplifier might sing. Danger of such singing is avoided with the critical frequency of the equalizer at the top operating frequency of the amplifier as shown by curve D.

As indicated above, features of importance in facilitating satisfactory operation of the amplifier over a wide range of frequencies extending up to high frequencies, include the interstage couplings resonant at the frequency of maximum line attenuation, and the circuit E, tuned to the frequency of maximum line attenuation, producing a gain-frequency characteristic such as curve B and a corrective phase shift such as indicated by curve D.

As indicated in the above mentioned copending application and in the above mentioned British patent, the negative feedback reduces phase distortion by reducing the overall amplifier phase shift throughout the operating frequency range as long as the value of $\mu\beta$ remains appreciable. This is of special importance in television work.

The amplifier is suitable for various uses, for example in television or in multiplex carrier telephony. It is capable of various modifications within the scope of the invention. For example, the bridges B_1 and B_2 may take any of a number of forms, for instance the bridge B_1 degenerating to merely a tapped resistance from the grid to the cathode. Various forms of tubes, with various numbers of elements in the tubes may be used. However, the use of elements II and II' is facilitated by the use of heat type tubes.

The invention claimed in the present application is an improvement on the invention claimed in the above-mentioned copending application Serial No. 606,871, which is the generic application.

What is claimed is:

1. A circuit, an amplifier associated therewith whose gain without feedback varies in a given manner over its operating frequency range, and means producing negative feedback in the amplifier of waves causing the gain of the amplifier with the feedback to vary similarly over the operating frequency range and equalize attenuation of said circuit.

2. The combination of an amplifier, a circuit associated therewith whose attenuation varies with frequency over an operating frequency range for said amplifier, and means forming with said amplifier a closed loop for producing negative feedback in the amplifier over said frequency range, said means comprising an attenuation equalizer for producing variation of the amplifier gain with frequency over said frequency range to compensate for variation of attenuation of said circuit with frequency, the phase shift of said loop exclusive of the phase shift of said equalizer passing through 180° in a given direction with increase of frequency at a given frequency at least substantially as high as the upper limit of said frequency range, and the phase shift of said equalizer passing through 0° in the opposite direction with increase of frequency at a frequency at least substantially as low as said given frequency.

3. An amplifier having a feedback path forming therewith a loop producing negative feedback therein, and a line attenuation equalizer in said path, the equalizer and the remainder of the loop having phase shifts of opposite sign, one decreasing its absolute magnitude rapidly from

large values to small values with increase of frequency from a given value, and the other increasing its absolute magnitude rapidly from small values to large values with decrease of frequency from approximately said given frequency.

4. An amplifier having a feedback path forming therewith a loop producing negative feedback therein, and a line attenuation equalizer in said path, the equalizer and the remainder of the loop having phase shifts of opposite sign, one decreasing its absolute magnitude rapidly from large values to small values with increase of frequency from a given value, and the other increasing its absolute magnitude rapidly from small values to large values with decrease of frequency from approximately said given frequency, and increasing its absolute magnitude rapidly from small values to large values with increase of frequency from approximately said given frequency.

5. An amplifier having a feedback path forming therewith a loop producing negative feedback therein, and a line attenuation equalizer in said path, the equalizer phase shift and the remaining phase shift of the loop respectively passing through 0° and 180° in opposite directions with frequency increase in the neighborhood of a given frequency, their arithmetic sum approximating 180° at a frequency in said neighborhood but their algebraic sum substantially differing from zero for all frequencies in said neighborhood.

6. An amplifier having a feedback path forming therewith a loop producing negative feedback therein, and a line attenuation equalizer in said path having a frequency of maximum attenuation, the equalizer phase shift at one neighboring frequency and the negative of the supplement of the remaining loop phase shift at another neighboring frequency being substantial relative to each other and of the same sign and having the sum of their absolute values at least substantially as great as 180° , and the algebraic sum of the equalizer phase shift and the remaining loop phase shift differing substantially from zero at every frequency in the frequency range of loop gain.

7. An amplifier having a feedback path forming therewith a loop producing negative feedback therein, and a line attenuation equalizer in said path having a frequency of maximum attenuation and having a maximum of negative phase shift and a maximum of positive phase shift at two frequencies respectively below and above said frequency of maximum attenuation, between said two frequencies the equalizer having values of phase shift relative to the phase shift of the remainder of the loop that increase the minimum departure of the total loop phase shift from zero between said two frequencies.

8. In an amplifier, a forwardly transmitting portion having its transmission without feedback vary with frequency over the utilized frequency range in accordance with a desired transmission-frequency characteristic, and a feedback path having its loss-frequency characteristic simulate said transmission-frequency characteristic and producing negative feedback in the amplifier for rendering the gain-frequency characteristic of the amplifier with feedback similar to said transmission frequency characteristic of said forwardly transmitting portion without feedback.