June 9, 1942. E. H. PERKINS 2,285,832

FEEDBACK AMPLIFIER

Filed April 20, 1940

FIG. 1

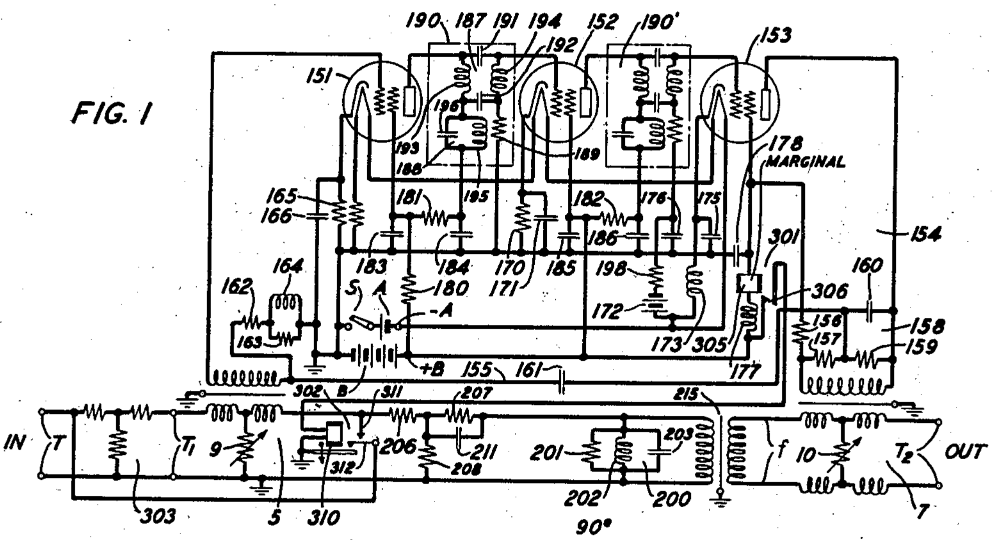


FIG. 3

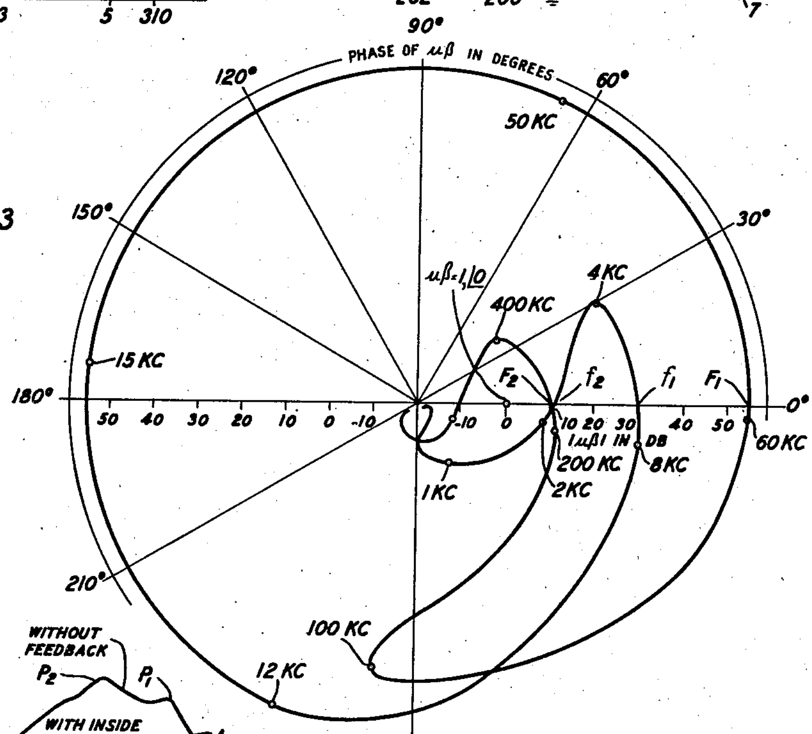
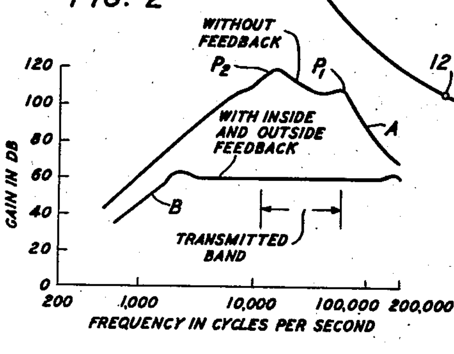


FIG. 2



INVENTOR
E. H. PERKINS
BY
B. L. Leger
ATTORNEY

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2,285,832

FEEDBACK AMPLIFIER

Edwin H. Perkins, Basking Ridge, N. J., assignor to Bell Telephone Laboratories, Incorporated, New York, N. Y., a corporation of New York

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17 Claims. (Cl. 179—171)

This invention relates to wave translation and especially to systems involving feedback amplifiers.

Objects of the invention are to control feedback and oscillations in such systems, to increase the width of transmitted frequency band obtainable in feedback amplifiers and the loop gain obtainable over the transmitted frequency band, to facilitate starting of conditionally stable feedback amplifiers or stable negative feedback amplifiers having loop phase equal to zero at a frequency for which the steady-state loop gain exceeds zero decibels, and to reduce deleterious effects upon amplifiers of such character caused by temporary overloads or other changes in operating conditions.

The usual stabilized feedback amplifier circuit (of a type disclosed, for example, in H. S. Black's paper on Stabilized Feedback Amplifiers, Electrical Engineering, January 1934 or in his Patent 2,102,671, issued December 21, 1937, or in H. W. Bode Patent 2,123,178, July 12, 1938) is designed to constitute a system that has been referred to as a "completely stable" system, in order to provide definite and preassigned gain and phase margins against singing. Provision of such margins ordinarily involves constructing the feedback loop or $\mu\beta$ loop so that the loop phase shift is not allowed to become zero for any frequency for which the loop gain equals or exceeds zero decibels, or in other words so that Φ is not allowed to become zero for any frequency for which $|\mu\beta|$ equals or exceeds unity. (Φ is the phase angle of the loop propagation $\mu\beta$, the symbols μ and β having the significance indicated in the above-mentioned paper and patents.) A stabilized feedback amplifier having what has been referred to as conditional stability (against oscillation) or Nyquist stability (in contradistinction to complete stability against oscillation) is disclosed in H. Nyquist Patent 1,915,440, June 27, 1933. The stability of such amplifiers, and of the feedback systems referred to herein in the specification and claims as conditionally stable, is conditional in the sense that since in normal stable operation there is a value of $\mu\beta$ for which $|\mu\beta|$ exceeds unity with $\Phi=0$, decrease of $\mu\beta$ to unity with this same phase angle can result in oscillation. Such decrease may occur, for example, because of decrease in transconductance of vacuum tubes in the circuit with time, due to the tubes becoming aged through use.

In stabilized feedback amplifiers, ordinarily a greater operating frequency range or a greater amount of negative feedback, or both, are attainable with conditional stability than with complete stability. However, special problems arise in connection with getting a conditionally stable amplifier into operation and maintaining this stable operation under varying operating conditions that may affect the loop gain, as for example varying load or varying power supply voltages.

For instance, in starting a conditionally stable negative feedback vacuum tube amplifier, that is, when first turning on the tubes or conditioning them for amplification, there may be a period in which the amplifier is unstable and starts singing (i. e. oscillating), before the temperatures of the cathodes of the tubes have reached their final values (i. e. their normal operating values) or while the transconductances of the tubes are building up or increasing toward their normal values after application of the energizing potentials for the tubes; also, because of some abnormal operating condition, as for example amplifier overload or temporary reduction of power supply voltage, the tube transconductances and consequently $|\mu\beta|$ may decrease, to such abnormal values that the amplifier becomes unstable and starts singing. In either case the singing may persist. That is, the singing so occasioned may continue after the amplifier has been turned on or after the overload or other abnormal operating condition has ceased.

A specific feature of the invention relates to the provision of means for automatically stopping such oscillations due to subnormal tube transconductance, upon their occurrence. For example, a relay responsive to changes of unidirectional space current of one of the tubes produced by the building up of the oscillations and by their decay may introduce sufficient loss or decrease of transmission efficiency in the feedback loop to stop the oscillations due to subnormal tube transconductance, upon their occurrence, and the relay may rapidly remove the loss, after the tube transconductance has become sufficiently high to render the amplifier stable with the loss removed, the removal of the loss being accomplished with sufficient rapidity to prevent oscillations from building up as the loop gain increases due to the loss removal. For instance, the relay may operate, upon the building up of oscillations, to cause a short circuit to be established across the feedback loop at some point in the loop so that the oscillations decay or cease, and the relay may operate, upon decay or cessation of the oscillations and consequent return of the unidirectional space current to approximately normal value and increase of tube transconductance to approximately normal operating value, to cause removal of the short circuit sufficiently rapidly to prevent oscillations from building up as the loop gain increases due to the removal of the short circuit.

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

In the drawing:

Fig. 1 is a circuit diagram of an amplifier embodying a form of the invention;

Fig. 2 shows gain-frequency characteristics of the amplifier; and

Fig. 3 shows the $\mu\beta$-characteristic of the amplifier or polar plot of the loop propagation $|\mu\beta|$, $\underline{/\Phi}$ over a frequency range extending from far below the operating range to far above the operating range.

Fig. 1 illustrates application of the invention to a feedback amplifier of the type employing repetition of feedback (a type disclosed, for example, in H. S. Black's above-mentioned Patent 2,102,671 and in his Patent 2,209,955, granted August 6, 1940, on copending application Serial No. 114,390, filed December 5, 1936, for Wave translation systems), with the repetition taking place through an outer feedback path *f* from an output hybrid coil 7 to an input hybrid coil 5. The amplifier comprises tandem connected tubes 151, 152 and 153, and has an output bridge 154 joining tube 153 to the hybrid coil 7 and to an inner feedback connection 155. This connection 155 applies the voltage from the bridge 154 across a feedback impedance in series with the secondary winding of the input hybrid coil with respect to grid-cathode impedance of tube 151.

The four ratio arms of the bridge 154 are the anode-cathode impedance of tube 153, resistances 156 and 157, and impedance 158. The arm 158 comprises a resistance 159 in parallel with a capacity 160 (of the order of 50 micro-micro-farads, for example) for controlling the slope of the attenuation-frequency characteristic of the inner feedback path, to control the phase shift above the transmitted band. The bridge 154 may be unbalanced, if desired, with resulting advantages brought out, for example, in H. S. Black Patent 2,131,365, September 27, 1938.

The feedback connection 155 includes a stopping condenser 161 for preventing passage of direct current through this connection. The feedback impedance in series with the secondary winding of hybrid coil 5 and included in the feedback diagonal of bridge 154 comprises two series connected elements; first, a feedback resistance 162; and second, a feedback resistor 163 in parallel with an inductance 164, this inductance serving to cancel the phase shift introduced by the blocking condenser 161 in the inner feedback path at low frequencies. A grid bias resistor 165 and by-pass condenser 166 are shown in the grid circuit of tube 151. Tubes 151 and 152 may be Western Electric Company type 310A tubes and tube 153 a Western Electric Company type 311A tube, for example. A 24-volt A battery or other suitable direct current source A with its positive pole grounded and its negative pole connected to the −A terminal supplies heating current to the filaments of tubes 151, 152 and 153 in series. A 130-volt B battery or other suitable direct current source B connected from ground to the +B terminal supplies space current for tubes 151 and 152, and these A and B sources in series supply space current for tube 153.

A grid bias resistor 170 by-passed by a condenser 171 supplies grid bias voltages for tube 152. Grid bias voltage for tube 153 is supplied through grid filter resistance 198 by grid biasing battery 172 and any direct current drop in inductance 173 which is in series with battery 172 and the direct current path from the cathode to the grid. This inductance serves, with condenser 175 which is a by-pass from the cathode of tube 153 to ground, as filter to prevent the alternating plate current of tube 153 from flowing through the A battery. Condenser 176 and resistance 198 filter the biasing voltage for the grid of tube 153; and the condenser 176 provides a by-pass around battery 172, resistance 198 and the A battery in series. A choke 177 and condenser 178 serve as a filter isolating the B battery with respect to alternating current; and condensers 175 and 178 by-pass alternating current between the cathode of tube 153 and the bridge arm 156. Resistance-capacity filters for the direct current plate supply circuits and screen grid biasing circuits of tubes 151 and 152 comprise resistors 180, 181 and 182 and capacities 183, 184, 185 and 186.

Fig. 2 shows the gain-frequency characteristics A and B of the amplifier of Fig. 1 between terminals T_1 and T_2 for operation without feedback and with feedback respectively, the particular amplifier for which these characteristics were measured being a 12- or 60-kilocycle transmitter amplifier for a twelve-channel cable carrier telephone system.

In this amplifier, tubes 151 and 152 are coupled by an interstage coupling network 190 comprising an air core or magnetic core transformer 187, a parallel-resonant circuit 188, a resistance 189, and stopping condensers or by-pass condensers 191 and 192. The transformer has a primary winding 193 and a secondary winding 194 which may have, for example, a 1:1 turns ratio, these windings being connected at one end by the stopping condenser 191, which connects the plate of tube 151 to the grid of tube 152, and at the other end by the condenser 192. Each of these condensers 191 and 192 may have a capacity of the order of .1 microfarad, for example. Resistor 189 is a grid leak having a resistance, for example, of the order of 60,000 ohms, providing a direct current path for biasing the grid of tube 152 without producing undue shunting effect upon the resonant circuit 188. This resonant circuit 188 is shown as a coil 195 and a capacity 196 which may be the self-capacity of the coil or may include a condenser separate from the coil. The interstage network 190 becomes parallel resonant with the interstage shunt capacity, including the self-capacity of the transformer, at a frequency in the neighborhood of the 60-kilocycle peak P_1 in curve A; and the resonant circuit 188 resonates at a frequency in the neighborhood of the 15-kilocycle peak P_2 in curve A. The transformer 187 renders the coupling impedance of the interstage network 190 high over the upper portion of the utilized frequency range and the resonant circuit 188 renders the impedance of the interstage network 190 high over the lower portion of the utilized frequency range, the two cooperating to maintain the impedance of the coupling circuit high over the whole of the utilized frequency range, to the end that the amplification of the amplifier without feedback may be high and not unduly variable with frequency over the utilized frequency range.

Tubes 152 and 153 are coupled by an interstage network **190'** structurally and functionally similar to the interstage network **190**. The frequency of the peak P_1 in curve A is determined by the resonance frequencies of transformer **187** and the corresponding transformer in network **190'**, and these resonance frequencies may differ somewhat. Similarly, the frequency of the peak P_2 in curve B is determined by the resonance frequencies of circuit **188** and the corresponding resonant circuit in network **190'**, and these two resonance frequencies may be staggered.

In the feedback path f is a deviation equalizer **200** comprising a parallel-connected resistance **201**, inductance **202**, and a capacity **203**, shunted across the path f. This deviation equalizer in the outer feedback path renders the over-all gain-frequency characteristic of the amplifier practically exactly flat over the utilized frequency range. For example, in the 12-kilocycle to 60-kilocycle transmitting amplifier for the twelve-channel cable carrier telephone system, this equalizer rendered the gain flat within about .01 decibel over the transmission band. Where it is desirable to be able to reduce the gain of an amplifier with feedback to as low a value as possible and an equalizer is to be used in the feedback path, it is advantageous to have the $\mu\beta$ loop include the input and output transformers in the general manner of Fig. 1, for example.

In the feedback path f is a network **205**, comprising resistances **206**, **207** and **208**, and the capacity **211**, which functions to increase the transmission loss in path f in the transmitted band of the amplifier, thus increasing the amplifier gain over that obtained with no transmission loss in the feedback path. The condenser **211** in parallel with resistance **207** is used to improve the phase shift at high frequencies and to decrease the loss of network **205** at frequencies above the utilized frequency range.

A transformer **215** which may have a turns ratio of 1:1, or any desired ratio, is shown in the feedback path f. The transformer improves the longitudinal balance of the system, and enables the circuits connected to its two windings to be one symmetrical and the other unsymmetrical (unbalanced-to-ground).

Fig. 3 shows the steady-state $\mu\beta$-characteristic of the amplifier (assuming the lines or terminating impedances attached at terminals T_1 and T_2 have the normal values of 600 ohms and 135 ohms respectively). This is the steady-state characteristic obtained, with both the inner and outer feedback paths effective, when the point at which the circuit is broken for measurement of loop propagation is a point of the μ-circuit or forwardly transmitting amplifying path common to both the inner and outer feedback paths (in contradistinction to a point of either feedback path).

This $\mu\beta$-characteristic shows that the loop phase shift is zero for four values of loop gain exceeding zero decibels. In other words, the characteristic crosses the real axis four times, with loop gain exceeding zero decibels, or the loop phase shift crosses through zero value at four frequencies for which $|\mu\beta|$ exceeds unity. Thus it may be said the characteristic has four cross-overs or cross-over points on the real axis for values of $|\mu\beta|$ exceeding unity. With frequency increase above a frequency in the operating frequency range at which $\Phi=180°$, there is a cross-over of the characteristic at frequency f_1 as the characteristic passes from the first quadrant into the fourth quadrant at a value of loop gain exceeding zero decibels, and with further frequency increase there is a cross-back as the characteristic passes from the fourth quadrant back into the first quadrant at frequency F_2 with $|\mu\beta|$ still exceeding unity. With frequency decrease below the frequency in the operating frequency range at which $\Phi=180°$, the characteristic has a cross-over point at frequency f_1 where it passes from the fourth quadrant into the first quadrant at a value of loop gain exceeding zero decibels, and with further frequency decrease the characteristic has a cross-back as it passes from the first quadrant back into the fourth quadrant at frequency f_2 with the loop gain still exceeding zero decibels.

(The amplifier of Fig. 1 as so far described may be, for example, that of Fig. 15 of the above-mentioned Patent 2,209,955.)

In a conditionally stable feedback amplifier, the problem of causing the amplifier to be stable when its vacuum tubes or amplifying elements have reached their steady-state operating conditions after application of their energizing potentials, for instance, application of filament heating potentials by switch S in Fig. 1 with the energizing circuits otherwise completed, and also the problem of causing the amplifier to be stable after an overload or other abnormal operating condition decreasing the loop gain sufficiently to render the amplifier unstable has been removed, arises if the steady-state $\mu\beta$-characteristic loops from the first quadrant into the fourth quadrant at high frequencies in the fashion indicated in Fig. 3, for example, or loops from the fourth quadrant into the first quadrant at low frequencies in the fashion indicated in Fig. 3, for example. This is because, in order for $|\mu|$ to reach its steady-state value, $\mu\beta$ must pass through a region of values which cause the $\mu\beta$-characteristic to enclose the point $1,\underline{/0}$, or in other words cause the amplifier to be unstable.

A solution for these problems lies in circuit additions shown in Fig. 1 as relays **301** and **302** and resistance pad or impedance correcting network **303**. Relay **301** has its winding connected in the unidirectional space current circuit of tube **153** and is adapted for marginal operation by unidirectional space current of that tube for causing its contact **306** to connect winding **310** of relay **302** across the battery B. Relay **302** is adapted to operate rapidly and release slowly. Contact **311** of relay **302** is for establishing a short circuit across the outer feedback path f of the amplifier. Contact **312** of relay **302** is for establishing a short circuit across the amplifier input terminals T to which is attached the incoming line or circuit.

The inner feedback path is such that with the outer feedback ineffective or inactive (for example, short-circuited by contact **311**) the amplifier is completely stable. That is, the amplifier can sing only when the outer feedback path **155** is active. The normal space current of the 311B tube **153** is 30 milliamperes. When the amplifier sings, the space current of this tube builds up to a value of approximately 55 milliamperes, which may be considered its normal singing value. This building up happens because the action of feedback is such that with full load output the space current seeks a value such that the voltage and current limitations of the tube will be realized together. This circuit is so adjusted that the "no load" space current is somewhat less than the "full load" value. When singing occurs, because of the fact that no limiting is incorporated into the circuit, the circuit will sing violently enough to operate the tube at full load output. Under normal service conditions, this full load output condition is not obtained except for instantaneous peaks, and the relay 301 will not respond for currents of such short duration. The relay 301 is adjusted to close its contact when a current of about 50 milliamperes flows in its winding 305 (so it will always receive sufficient current for operating it when oscillations build up in the amplifier to a steady-state amplitude), and this relay is adjusted to release its contact when the current decreases to about 35 milliamperes. The contacts of relay 302 are so associated that, in opening, they open the short circuit across the feedback path *f*, first, and the short circuit across the input terminals T afterward. That is, contact 311 opens before contact 312.

The operation of starting the amplifier or turning on the tubes to condition them for amplifying will now be described. During this operation the amplifier may be disconnected from the incoming and outgoing lines, if desired.

When switch S is operated to its closed position the two 310A tubes 151 and 152 come up to normal transconductance in about a minute, but in that time the transconductance of the 311A tube 153 has reached only about 100, or such a fraction of its normal transconductance as to make the $\mu\beta$-characteristic of the amplifier enclose the point 1,/0 and therefore make the amplifier start to sing. As the cathode of tube 153 continues to increase in temperature, the space current of the tube increases toward its normal singing value of 55 milliamperes. After about three minutes it reaches a value (about 50 milliamperes) sufficient to operate relay 301. Relay 301 then closes its contact, causing relay 302 to close contact 311 to establish a short circuit across the feedback path *f*. The singing condition then no longer exists. Therefore, as the sing transient dies out $|\mu|$ increases to its normal operating value and the space current of tube 153 decreases to its normal operating value of 30 milliamperes, so relay 301 releases its contact, causing relay 302 to open the short circuit across the feedback path *f* and bring the amplifier to its normal operating condition. Relay 302 is made a slow-releasing relay, since the increase of $|\mu|$ to its normal operating value may be slower than the decrease of the space current to its normal operating value and so if the relay releases too quickly the singing condition may not be cleared before the feedback path is again rendered operative. A "hunting" condition might thus be established if the relay were not a slow-release relay.

In starting the amplifier as just described, with the amplifier not connected in the transmission line or circuit, the short-circuiting of the amplifier input terminals T is not necessary. However, when the feedback path *f* is operative, the amplifier may sing if the impedance viewed from the input terminals T_1 of the hybrid coil 5 when looking toward terminals T differs too greatly from the normal value (which may be 600 ohms). For example, if the impedance so viewed from terminals T_1 is zero or infinity, (the values of $\mu\beta$ given by Fig. 3 do not obtain and) such improper value of impedance may cause the amplifier to sing. The impedance correcting network 303 insures that, even with terminals T open-circuited or short-circuited, the impedance so viewed from terminals T_1 will not differ from its normal value sufficiently to cause such singing.

The normal load impedance for the amplifier may be 135 ohms, for example. If the amplifier is to be started as described above with the amplifier not connected in circuit, it may be necessary to consider the effect of an infinite load impedance (i. e., an open-circuit condition at terminals T_2) in the design of the amplifier to insure against possibility of singing. However, if bridge 154 is in passive balance and the impedance of hybrid coil 7 facing bridge 154 balances impedance 10, so that the load is conjugate to the feedback path *f*, then the load impedance does not affect stability of the amplifier against singing.

The operation of the amplifier under overload will now be described. As indicated by the $\mu\beta$-characteristic in Fig. 3, if the amplifier is so overloaded as to cause $|\mu|$ to decrease by about 10 decibels or more, a singing condition exists; and the singing persists after the load signal falls below the overload value (or, in other words, the amplifier locks into the singing condition) unless the amplifier is controlled. It is controlled as follows: When the singing starts, the space current of tube 153 increases to 50 milliamperes or more, relay 301 operates and causes relay 302 to short-circuit the feedback path *f* and the input terminals T so the singing dies out according to its transient response and subsequently the relay 301 releases its contact upon the restoration of the space current of tube 153 to normal operating value. Relay 302 is thereby deenergized. It opens its contact 311 thus bringing the amplifier to its normal operating condition, and thereafter it opens its contact 312 thus removing the short circuit across terminals T.

If the overload has vanished when the cycle of operation is thus completed, the operation of the amplifier is normal. The complete cycle may take less than a second of time when caused by a peak overload of short duration. An instantaneous peak such as exists in speech will not cause the relay 301 to operate, because the full load space current it causes exists for too short a time to operate the relay.

If, on the other hand, a continued overload is present, the cycle of operation is repeated until the overload is removed. Repeated operation of the relay cycle can be caused to bring up a circuit alarm if desired for example, by having relay 301 also operate a counting relay, not shown, which will introduce an alarm after any desired number of cycles of operation of relay 301. Such an alarm is desirable because if the amplifier were permitted to continuously repeat this relay cycle, it would indicate a circuit trouble and also the continuing cycle of operation would constitute a circuit interruption.

The sequence in which the contacts of relay 302 open insures that the short circuit across the feedback path *f* will always be removed before the short circuit across the terminals T is removed. Otherwise the normal full load input would effectively be too high; for with the short circuit across *f* removed, the feedback through path *f* may reduce the amplifier gain 15 decibels, for example, and with a short circuit established across the feedback path *f* the amplifier which, without the short circuit across *f*, may have a normal gain of 55 decibels, for example, has a gain of 70 decibels.

In the operation of the amplifier upon occurrence of overload, when terminals T are short-circuited, a singing condition might exist because of this short circuit if network 303 were not present. Then as soon as the feedback path

f was rendered operative by the opening of contact **311**, the amplifier instead of being stable would be unstable and so the relays would "hunt" as with a sustained overload. This difficulty is overcome by the use of the network **303** between the short circuit at terminals T and the terminals T_1. As indicated above, the network presents the proper impedance to terminals T_1, notwithstanding the short circuit across the terminals T to prevent input signals from entering the amplifier. The transmission loss in the network **303** may be of the order of 3 decibels, for example.

When the amplifier is started while it is connected in a transmission circuit, the short circuit across terminals T is advantageous in preventing any shock excitation entering the amplifier from the input line or circuit that might tend to set the amplifier singing when the short circuit across the feedback path f is first opened.

Although the slow-release characteristic of relay **302** is advantageous as indicated above, the removal of the short circuit across the feedback path by contact **311**, once started, should be effected rapidly enough to increase $|\mu\beta|$ through its unstable region of values in a time so short that oscillations cannot build up to amplitudes that would limit $|\mu|$, for example, by causing grid current flow, or that would cause the space current of tube **153** to rise sufficiently to operate relay **301**.

Impedance levels ordinarily are lower in the feedback path than in the μ-circuit. Consequently, locating the short circuit for the $\mu\beta$ loop path in the feedback path rather than in the μ-circuit is advantageous in minimizing deleterious effects of capacity introduced across the loop path by the short-circuiting means. However, the low impedance of the feedback path tends to increase difficulty of effectively short-circuiting the feedback voltage. The amplifier using repetition of the feedback process, with the inner and outer feedback paths, is advantageous in facilitating effective short-circuiting action of the means for establishing the short circuit across the outer feedback path; for example, the total reduction of the insertion gain of the amplifier to be effected by feedback may be 55 decibels, of which 40 decibels may be obtained by the inner feedback path, leaving only 15 decibels to be effected by the outer feedback path, so the feedback voltage to be short-circuited across the feedback path is relatively small and is therefore relatively easy to short-circuit effectively. In other words it is advantageous to employ an amplifier, of the type shown in Fig. 1, using a repetition of the feedback process, with inner and outer feedback paths, and with the amplifier completely or unconditionally stable when only the inner feedback path is active, because under this condition only the portion of the $|\mu\beta|$ gain represented by the increase in $\mu\beta$ due to the looped-over portion of the $\mu\beta$-characteristic need exist in the outer feedback loop, and this reduces the approach to an absolute short circuit necessary to accomplish the desired result. As just indicated, in the case of the amplifier of Fig. 1, the total $|\mu\beta|$ was about 55 decibels but that effective in the outer path was only about 15 decibels.

The amplifier, using repetition of the feedback process, with a considerable portion of the total negative feedback obtained by the inner feedback path, is also advantageous in reducing shock excitation that might occur due to removal of the short circuit across the outer feedback path and start the amplifier singing; for decreasing $|\mu\beta|$ decreases the shock.

If desired, filters (not shown) for suppressing waves of singing frequency may be used to connect terminals T and T_2 of the amplifier to its attached incoming and outgoing circuits, for excluding the oscillations of the singing frequencies from those circuits. Either filter, or both, may be omitted, depending upon the specific application of the amplifier.

Also, if desired, a voltage limiter (not shown) may be connected between the incoming line and terminals T, to reduce danger of overload causing the amplifier to start singing. It may be of any suitable type, as for example, a negative feedback amplifier with its gain-load characteristic having a shart cut-off, as in the case of Fig. 10 of the above-mentioned paper of H. S. Black, the overload point or cut-off value of load being adjusted, for example, to a load value sufficiently low to insure that the input to terminals T cannot reach a value so large as to cause the $\mu\beta$-characteristic of Fig. 3 to shrink in such manner as to pass through or enclose the point $1,\underline{/0}$.

In a conditionally stable amplifier, such as the amplifier of Fig. 1, for example, if $|\mu\beta|$ is to be varied, for instance, by varying the attenuation of network **205** to vary the insertion gain of the amplifier by changing the β-circuit loss and thus the amount of feedback, the decibel spread in Fig. 3 between the point $\mu\beta=1,\underline{/0}$ and the first cross-over to the right should be adequate to prevent the $\mu\beta$-characteristic from enclosing the point $\mu\beta=1,\underline{/0}$ when the loss in the feedback path f is adjusted to its maximum value.

The shunt across path f, controlled by contact **311**, need not in all cases have zero impedance. It should, when closed, render the amplifier completely stable. In other words, it should be capable of changing the amplifier from a conditionally stable state to a completely stable state.

In the claims "stable" is used in the sense that the response, to a small impressed force which dies out in the course of time, also dies out. A well-known criterion for this stability is Nyquist's rule. One way of stating the rule gives as the necessary and sufficient condition for stability the requirement that the graph of the imaginary part of the loop propagation or transfer factor around the feedback loop plotted against the real part for all real values of frequency avoid encircling the point 1,0.

In the expression "conditionally stable" appearing in the claims, "stable" has the significance just indicated, and "conditionally" signifies that the stability is conditional in the sense above indicated.

What is claimed is:

1. A wave translating system comprising an electric space discharge wave amplifying device, means forming with said device a feedback loop adapted to produce feedback with the loop gain exceeding zero decibels for a frequency at which the loop phase shift is zero and with the graph of the imaginary part of the loop propagation plotted against the real part for all real values of frequency avoiding encircling the point 1,0, and means responsive to a direct current component of space current of said device for controlling the loop propagation.

2. An amplifier comprising a vacuum tube amplifying device, a feedback path therefor forming therewith a feedback loop for producing feed-

back that renders the amplifier conditionally stable, and means responsive to change in steady space current of said amplifying device for establishing a high admittance across the feedback loop.

3. An amplifier comprising a vacuum tube amplifying device, a feedback path therefor forming therewith a feedback loop for producing feedback that renders the amplifier conditionally stable, a low impedance path for connection across said feedback loop to form a low impedance shunt across said feedback loop, and means controlled by a direct current component of space current of said amplifier for controlling connection of said low impedance path across said feedback loop.

4. An amplifier comprising a vacuum tube amplifying device, a feedback path therefor forming therewith a feedback loop for producing feedback that renders the amplifier conditionally stable, means for forming a low impedance shunt across said feedback loop, and means controlled by direct space current of said amplifier for removing said shunt.

5. An amplifier comprising a vacuum tube amplifying device, a feedback path therefor forming therewith a feedback loop for producing feedback that renders the amplifier conditionally stable, and means responsive to change of direct space current of said amplifier caused by building up of transient self-sustained oscillations around the feedback loop for preventing said transient oscillations from producing steady-state oscillations around said loop.

6. An amplifier comprising a vacuum tube amplifying device, a feedback path therefor forming therewith a feedback loop for producing feedback that renders the amplifier conditionally stable, and means responsive to change of steady space current of said amplifier caused by overloading of the amplifier for preventing steady-state oscillations around said loop from being produced by transient oscillations caused by said overloading.

7. An amplifier comprising a vacuum tube amplifying device, a feedback path therefor forming therewith a feedback loop for producing feedback that renders the amplifier conditionally stable, contacts for establishing a low impedance shunt across the loop, a plate circuit for said amplifying device, and means comprising a winding in said plate circuit for operating said contacts upon the building up of self-sustained oscillations around the loop.

8. An amplifier comprising a vacuum tube amplifying device, a feedback path therefor forming therewith a feedback loop for producing feedback and with the graph of the imaginary part of the loop propagation plotted against the real part for all real values of frequency avoiding encircling the point 1,0 with loop gain exceeding zero decibels at a frequency of zero loop phase shift, a circuit for supplying unidirectional space current to said amplifying device, and means for preventing establishment of a steady-state sing around the feedback loop comprising relay apparatus including contacts for establishing a low impedance shunt across said feedback loop, a relay winding connected in said unidirectional space current circuit of said amplifying device, and means controlled by energization of said winding for controlling operation of said contacts.

9. An amplifier comprising a vacuum tube amplifying device, a feedback path therefor forming therewith a feedback loop whose loop gain exceeds zero decibels for two frequencies at which the loop phase shift changes sign at zero degrees and whose loop propagation has the graph of its imaginary part plotted against its real part for all real values of frequency avoid encircling the point 1,0, a circuit for supplying unidirectional space current to said amplifying device, and means for preventing establishment of a steady-state sing around the feedback loop upon energization of said amplifying device to condition said device for amplifying, comprising relay apparatus including contacts for establishing a low impedance shunt across said feedback loop, a relay winding connected in said unidirectional space current circuit of said amplifying device, and means operated by energization of said winding upon energization of said amplifying device for controlling operation of said contacts.

10. An amplifier and an incoming circuit therefor, said amplifier comprising a vacuum tube amplifying device, a feedback path therefor forming therewith a feedback loop for producing feedback that renders the amplifier conditionally stable, and means for preventing establishment of a steady-state sing around the feedback loop upon occurrence of overload of the amplifier, comprising means responsive to change in direct space current of said amplifying device for establishing a low impedance shunt across the feedback loop and introducing a large transmission loss between the incoming circuit and the amplifying device.

11. An amplifier comprising a vacuum tube amplifying device, a feedback path therefor forming therewith a feedback loop for producing feedback that renders the amplifier conditionally stable, and means responsive to change of steady space current of said amplifier from its normal value caused by building up of self-sustained oscillations around the feedback loop for establishing a low impedance shunt across said feedback loop and responsive to restoration of said unidirectional space current to its normal value for removing said shunt.

12. An amplifier comprising a vacuum tube amplifying device, a feedback path therefor forming therewith a dynamically stable feedback loop having loop gain so great over a frequency band so wide that the loop phase shift is zero at a frequency for which the loop gain exceeds zero decibels, a relay responsive to increase of a direct current component of space current of said amplifying device produced by building up of self-sustained oscillations around the loop upon energization of said amplifying device to condition said device for amplifying, and means controlled by said relay for placing a low impedance shunt across said path.

13. An amplifier comprising a vacuum tube amplifying device, a feedback path therefor forming therewith a dynamically stable feedback loop having loop gain decrease so rapidly with change of frequency at one side of the operating frequency range of the amplifier that before the decreasing loop gain reaches zero decibels the loop phase changes sign at zero degrees, a switch operable for placing a low impedance shunt across said feedback path, and means for closing said switch to shunt said feedback path in response to increase of unidirectional space current of said amplifying device above its normal value produced by building up of self-sustained oscillations around the feedback loop of the amplifier upon energization of said amplifying device and for releasing said switch from its closed condition to remove said shunt in response to

decrease of said space current to its normal value upon cessation of said oscillations.

14. An amplifier comprising an electronic wave amplifying device, a feedback path from the output of said device to the input of said device adapted to form with said device a dynamically stable feedback loop having loop propagation whose graph of imaginary part versus real part for all real values of frequency avoids encircling the point 1,0 and having loop gain so great over a frequency band extending so far upwardly from a frequency at which the loop phase shift is 180 degrees that before the loop gain decreases to zero decibels with frequency increase above said band the loop phase shift decreases to zero degrees, means introducing transmission loss in said loop when the gain of said amplifying device has a subnormal value and means responsive to a steady current component of space current of said device after increase of its gain above said subnormal value for removing said loss.

15. An amplifier comprising a vacuum tube amplifying device, a feedback path therefor forming therewith a feedback loop for producing feedback that renders the amplifier conditionally stable, a space current supply circuit for said amplifying device, said amplifying element increasing its unidirectional space current in said space current supply circuit above the normal operating value when self-sustained oscillations build up around the feedback loop upon energization of said amplifying device, a relay operable to closed position when energized for short-circuiting said feedback path, and a relay having a winding in said space current supply circuit for energizing said first-mentioned relay in response to said increase of space current and for deenergizing said first-mentioned relay to remove said short circuit in response to decrease of said space current to its normal value upon cessation of said oscillations.

16. An amplifier and an incoming circuit therefor, said amplifier comprising a vacuum tube amplifying device, a feedback path therefor forming therewith a feedback loop for producing feedback that renders the amplifier conditionally stable, means for preventing establishment of a steady-state sing around the feedback loop upon occurrence of overload of the amplifier, comprising means responsive to change of unidirectional space current of said amplifier from its normal value for establishing a low impedance shunt across the feedback loop and introducing a large transmission loss between the incoming circuit and the amplifying device and responsive to restoration of said unidirectional space current to its normal value for removing said shunt, said first-mentioned means comprising also an impedance device terminating said amplifier at its input side when said loss is introduced in an impedance of proper value to prevent said amplifier from singing due to improper impedance termination when said shunt is removed.

17. An amplifier comprising an electronic wave amplifying device, two conjugate feedback paths therefor, one of said paths having propagation that renders the amplifier conditionally stable when the gain of said device is normal and tends to produce steady state oscillation of said amplifier when the gain of said device is subnormal and means for counteracting said tendency comprising means to control propagation of said one of said paths and means responsive to a direct current component of space current of said device for controlling said propagation control means.

EDWIN H. PERKINS.