

Aug. 6, 1940.

E. H. PERKINS

2,210,001

ELECTRIC WAVE AMPLIFYING SYSTEM

Filed Dec. 5, 1936

2 Sheets-Sheet 1

FIG. 1

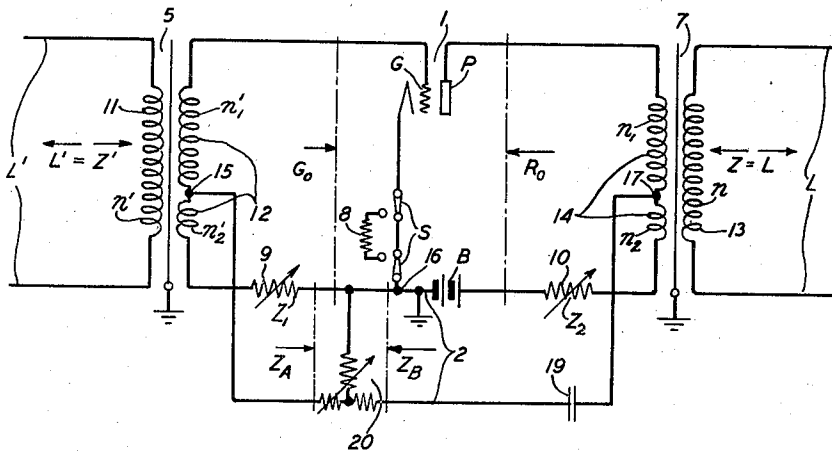
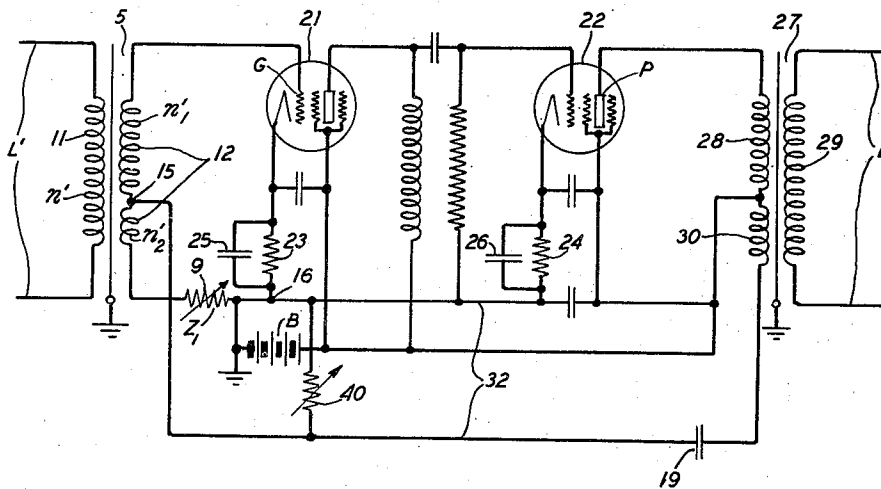


FIG. 2



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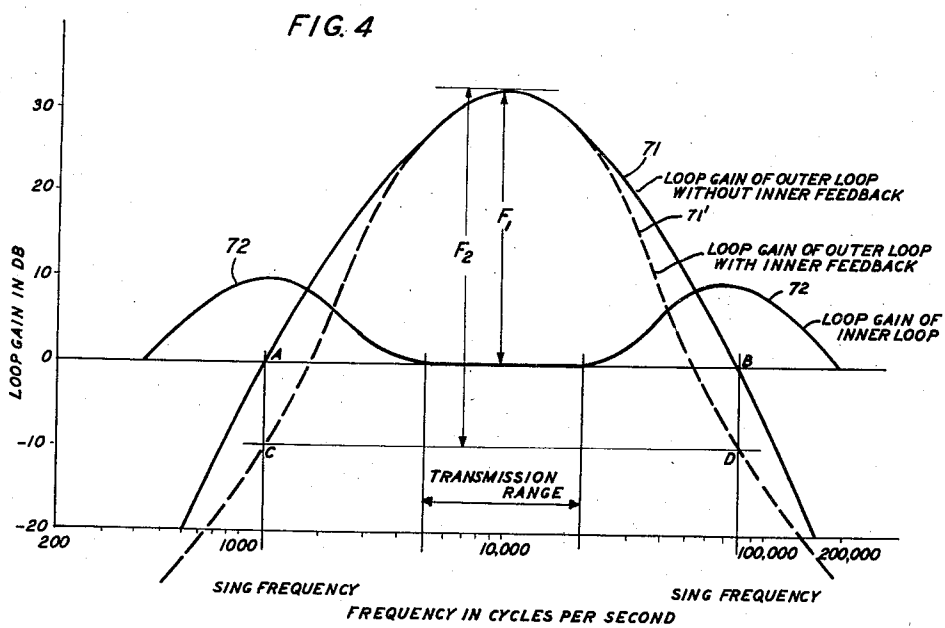
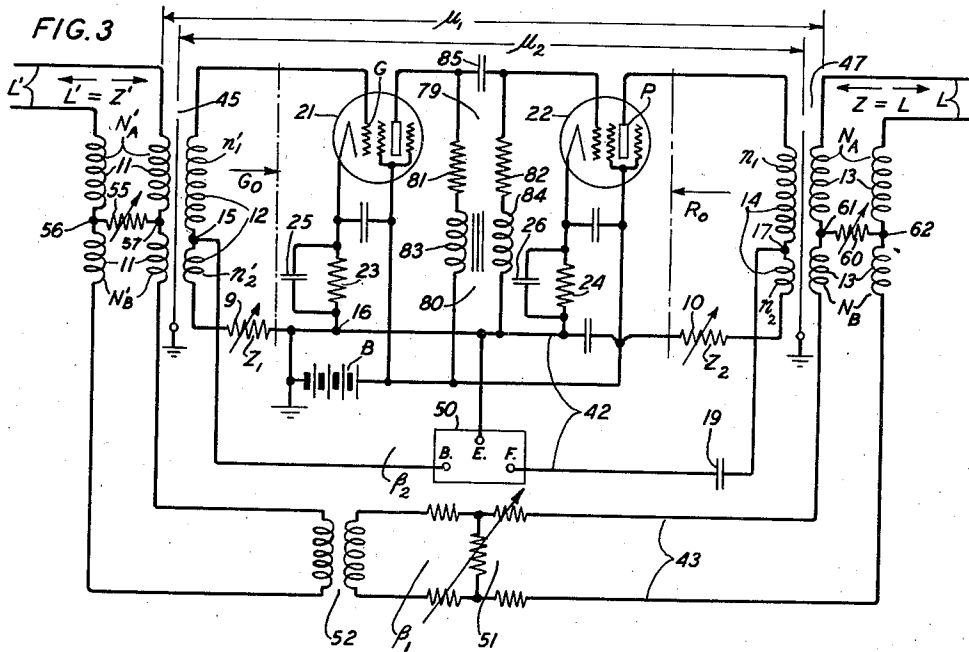
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ELECTRIC WAVE AMPLIFYING SYSTEM

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2 Sheets-Sheet 2



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UNITED STATES PATENT OFFICE

2,210,001

ELECTRIC WAVE AMPLIFYING SYSTEM

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Application-December 5, 1936, Serial No. 114,393

14 Claims. (Cl. 179-171)

This invention relates to wave translation, and relates especially to wave amplifying systems involving feedback action.

An object of the invention is to control transmission properties of such systems, as for example, to control impedances and reduce longitudinal currents in such systems.

It is also an object of the invention to control feedback and facilitate application of feedback in such systems.

The feedback may be, for instance, feedback of a portion of the output waves of a system in gain-reducing phase and in amount sufficient to reduce distortions below the distortion level without feedback. Such feedback is disclosed, for example, in the copending application of H. S. Black, Serial No. 606,871, filed April 22, 1932, for Wave translation system, which issued December 21, 1937, as Patent 2,102,671, and in the article by H. S. Black on Stabilized feedback amplifiers, published in Electrical Engineering, January 1934, pages 114 to 120.

In one specific aspect the invention is an amplifier having an amplifying path and a path which produces such feedback, with a hybrid coil serving as an input or output transformer connecting the amplifier to an incoming or outgoing line, the hybrid coil having a divided winding and an inductively related winding, with one part of the divided winding connected between the amplifying path and the feedback path and the other part connected between the feedback path and the balancing network of the hybrid coil, the inductively related winding or low impedance winding of the input or output transformer being connected to the line.

If desired, one such hybrid coil connection can be used at the input of the amplifier for associating the input end of the amplifying path with the incoming line and the feedback path, and another such hybrid coil connection can be used at the output of the amplifier for associating the output end of the amplifying path with the outgoing line and the feedback path.

With such hybrid coil connection to an incoming or outgoing line the amplifier need not be conductively connected to the line, and the line may be either balanced or unbalanced with respect to ground even though the amplifier be unbalanced with respect to ground. With such hybrid coil connection at the amplifier input and at the amplifier output, either line, or both, can be unbalanced with respect to ground and at the same time substantial longitudinal attenuation can be obtained between the lines.

Such hybrid coil connection not only gives substantial attenuation of longitudinal currents from outgoing line to incoming line and vice versa, but further, with such hybrid coil connection at the amplifier output, objectionable longitudinal currents transmitted to the input of the amplifier from the output line and returned to the output line are reduced by the feedback action. In like manner, such a hybrid coil connection at the amplifier input causes the objectionable longitudinal currents existing there to be reduced by feedback.

With such hybrid coil connection of the amplifier to a line, the negative feedback is applied to the amplifier effectively through the input or output transformer, and the transformer is included in the μ -circuit or forwardly transmitting portion of the feedback loop, so modulation and other distortion introduced by the transformer is reduced by the feedback action. As a result, the modulation requirements and other distortion requirements of the transformer will be less severe and, in general, the transformer will be cheaper to build and will be able to provide much higher gain when desired.

Also, with such hybrid coil connection of the amplifier to a line, when considerable amounts of negative feedback are used the amplifier impedance facing the line can be adjusted or set by adjustment of the value of the impedance of the balancing network of the hybrid coil. Moreover, such adjustment need not materially affect the impedance faced by the amplifying element. For example, in the case of a vacuum tube amplifier, the impedance of the balancing network of the output hybrid coil can be varied to vary the amplifier output impedance while working the last tube into its optimum value of load impedance.

Further, the adjustment of the amplifier impedance by adjustment of the balancing network need not materially disturb conjugacy of the line and feedback path; for the feedback tends to give such conjugacy regardless of whether such conjugacy would exist without feedback; and considerable amounts of negative feedback maintain this conjugacy even when the impedance of the balancing network is varied widely.

A second feedback path may be connected to the low impedance windings of the input and output transformers; and, considering for example, the output side of the amplifier, this feedback path may be made conjugate to the outgoing line by dividing the low impedance winding of the output transformer into two parts, providing a

balancing network for balancing the impedance facing the other divided winding of the hybrid coil or output transformer, and connecting one part of the low impedance winding between the outgoing line and this balancing network and connecting the other part between this network and the second feedback path. This network can then be adjusted to adjust or set the amplifier output impedance in the general manner disclosed in the application of H. S. Black, Serial No. 114,390, for Wave translation systems, filed of even date herewith. Such adjustment of this network need not materially disturb conjugacy of the line and the second feedback path, for the feedback through the second feedback path tends to give such conjugacy regardless of whether such conjugacy would exist without feedback and with considerable amounts of negative feedback this conjugacy is approached even when the impedance of the balancing network is varied widely. The feedback through the first feedback path (i. e., inner feedback path) facilitates obtaining the conjugacy between the second feedback path and the outgoing line; for that feedback stabilizes the impedance that must be balanced by this balancing network in order to obtain this conjugacy (i. e., the impedance, with feedback, facing the high impedance winding of the transformer or high impedance divided winding of the hybrid coil).

The feedback through the second feedback path is applied to the amplifier through the transformer or hybrid coil. That is, the transformer is included in the μ -circuit or forwardly transmitting portion of the feedback loop formed by the amplifying path and this feedback path, so distortion introduced by the transformer is reduced by the feedback through the second feedback path.

At the input side of the amplifier the interconnections of the amplifying path, the incoming line and the feedback paths may be similar to the interconnections just described with reference to the output side of the amplifier for the amplifying path, the outgoing line and the feedback paths. Likewise, similar advantages result.

A transformer may be connected in the second feedback path between the output and input hybrid coils. It may be a unity ratio transformer or a transformer having any suitable turns ratio or impedance ratio. With this transformer in the second feedback path, the circuits respectively attached to its primary and secondary windings may be both unsymmetrical with respect to ground (i. e., unbalanced-to-ground), or both balanced-to-ground, or either one balanced and the other unbalanced with respect to ground. Each of the transformers in the feedback loop can have its transmission band width, or in other words, its cut-off frequencies, so related to the transmission band widths or cut-off frequencies of the other transformers in the loop as to reduce singing tendency in the amplifier as indicated hereinafter.

When the two feedback paths are provided, a band elimination filter attenuating waves of a frequency range including the transmission frequency range of the amplifier may be connected in the first feedback path, for controlling the relative amounts of feedback through the two feedback paths, to reduce singing tendency in the amplifier or increase the amount of negative feedback permissible, as indicated hereinafter.

Other objects and aspects of the invention will

be apparent from the following description and claims.

Fig. 1 shows schematically an amplifier circuit embodying a form of the invention;

Figs. 2 and 3 are circuit diagrams of amplifiers embodying other forms of the invention; and

Fig. 4 shows curves for explaining operation of the amplifier of Fig. 3.

The amplifier of Fig. 1 may be a stabilized feedback amplifier circuit of the general type disclosed in the Patent 2,102,671 and published article which are referred to above. It comprises an amplifying path which may be, for example, an amplifying element 1 of the vacuum tube type having a single vacuum tube stage or any desired number of tandem connected stages, G and P designating the grid of the first tube and the plate of the last tube. It comprises also a feedback path 2. The amplifying path or element may be referred to as the μ -circuit and the feedback path may be referred to as the β -circuit, the significance of μ and β and μ -circuit and β -circuit being as indicated in the application and article just mentioned.

An input hybrid coil 5 serves as an input transformer coupling the incoming line or circuit L' and the feedback path 2 to the input end of the amplifying path and an output hybrid coil 7 serves as an output transformer coupling the output end of the amplifying path to the outgoing line or circuit L and the feedback path.

The impedance presented by the input end of the amplifying path is designated G_0 , and the impedance presented by the output end of the amplifying path is designated R_0 . If desired, an impedance 3 may be inserted in the connection from the cathode structure to the grid circuit of the first tube and the plate circuit of the last tube by means of switches S, for example, to provide negative feedback raising the impedance G_0 . The impedance 3 may be, for instance, a resistance raising the impedance G_0 by feedback and also furnishing part or all of the grid bias for the first tube.

The input transformer or hybrid coil 5 has a low impedance winding or primary winding 11 of n' turns, which is inductively related to a winding 12. The winding 12 is the high impedance winding or secondary winding of the input transformer and is composed of two parts n'_1 and n'_2 . The winding n'_1 has n'_1 turns and the winding n'_2 has n'_2 turns.

The output transformer or hybrid coil 7 has a low impedance winding or secondary winding 13 of n turns, which is inductively related to a winding 14. The winding 14 is the high impedance winding or primary winding of the output transformer and is composed of two parts n_1 and n_2 . The windings n_1 and n_2 have n_1 turns and n_2 turns respectively.

The amplifier input impedance Z' may match the impedance L' of the incoming line and the amplifier output impedance Z may match the load impedance L. The hybrid coil 5 has a balancing network 9 of impedance Z_1 for balancing the impedance G_0 ; and the hybrid coil 7 has a balancing network 10 of impedance Z_2 for balancing the impedance R_0 . However, negative feedback through path 2 tends to render the incoming line conjugate to the feedback path, and considerable amounts of such feedback give practical conjugacy, even though, for the values of n'_1 , n'_2 and n' obtaining in the circuit, the impedance Z_1 be not of the value that would be required for producing such conjugacy without

the feedback. Similar considerations hold at the output of the amplifier, with respect to the outgoing line, the feedback path and the hybrid coil 7 with its network 10. With considerable amounts of negative feedback through path 2, the amplifier input impedance Z' asymptotically approaches the value

$$Z' = K_1 Z_1 \text{ where } K_1 = \frac{(n')^2}{n'_1(n'_1 + n'_2)}$$

Similarly, with considerable amounts of the negative feedback, the amplifier output impedance Z asymptotically approaches the value

$$Z = K_2 Z_2 \text{ where } K_2 = \frac{n^2}{n_1(n_1 + n_2)}$$

It is seen that the amplifier impedances Z' and Z are independent of the impedances Z_A and Z_B of the feedback path viewed from the bridge points 15 and 16 of the input hybrid coil circuit and the bridge points 17 and 16 of the output hybrid coil circuit, respectively. The value of the input impedance Z' , with considerable amounts of negative feedback, is equal to the value that the primary-to-secondary impedance of the input transformer 5 would have, with or without feedback, if the impedance G_0 were of such value as to produce zero voltage across the bridge points 15 and 16 of the input hybrid coil circuit. Similarly, the value of the output impedance Z , with considerable amounts of negative feedback, is equal to the value that the secondary-to-primary impedance of the output transformer 7 would have, with or without feedback, if the impedance R_0 were of such value as to produce zero voltage across the bridge points 17 and 16 of the output hybrid coil circuit.

With considerable amounts of negative feedback through the path 2, the impedance Z_1 can be adjusted to adjust the amplifier input impedance, for example to match the amplifier input impedance to the impedance L of the incoming line, without disturbing conjugacy between the incoming line and the feedback path; and similarly, the impedance Z_2 can be adjusted to set the value of the amplifier output impedance without disturbing the conjugacy between the outgoing line and the feedback path. With considerable amounts of negative feedback through the path 2, the impedance Z is not affected by variations of μ or R_0 due for example to changing tubes or types of tubes; and similarly, Z' is independent of μ and G_0 .

The control of impedance Z' by impedance Z_1 is advantageous for example for increasing the ratio of signal to resistance noise level in the amplifier output while maintaining Z' matched to L , in the general manner brought out in the above-mentioned application filed of even date herewith. That is, the value that Z' would have without feedback can be made much higher than L' to increase the signal-to-noise ratio at the input grid, with Z_1 adjusted so that the feedback lowers Z' to match it to L' .

The control of impedance Z by impedance Z_2 is advantageous for example for matching Z to L while working the last tube of the amplifier into its optimum load impedance, without undue transmission loss, in the general manner brought out in the above-mentioned application filed of even date herewith.

The feedback path 2 is shown as comprising a stopping condenser 19 and a transmission control network 20 of generalized impedances. The network 20 may be for example, of the constant-R

type. It may be used for controlling the gain of the amplifier. With considerable amounts of feedback through path 2, the gain of the amplifier can be varied by variation of the transmission efficiency of the network 20, increase of its transmission efficiency decreasing the amplifier gain, and vice versa. The network 20 may be, for example, a transmission equalizing network, or a network for controlling the phase shift produced by the amplifier, or a network for controlling the value of $\mu\beta$ in order, for instance, to facilitate prevention of singing around the feedback loop comprising path 2. With considerable amounts of negative feedback through path 2 then regardless of whether the impedances Z_A and Z_B of the network are constant, adjustment or variation of the network will not affect the amplifier input impedance Z' or the amplifier output impedance Z .

The tap at 15 in the winding 12 of hybrid coil 5, and likewise the tap at 17 in the winding 14 of hybrid coil 7, may divide the winding unevenly and still maintain the hybrid balances. This provides a means of getting both a low impedance for the feedback circuit and a high impedance to face the tube grid. The displacing of the tap from the center of the winding also aids in getting more gain from a given number of turns on the coil winding, as a greater proportion of it is active in the grid circuit of the tube.

The form of hybrid coil connection shown in Fig. 1 maintains its hybrid balances or the conjugacies between the line and the feedback circuit by virtue of the mutual impedance of the coil windings being sufficient so as not to affect the transmission between these circuits. If conjugacy is desired at a frequency where the inherent mutual impedance is not sufficient to produce the desired hybrid balance, it can be obtained by terminating the coil by the proper complex impedances, as Z_1 and Z_2 .

Fig. 2 shows an amplifier circuit which is a modification of the circuit of Fig. 1, the feedback connection at the output side of the amplifier being an inductive shunt feedback connection instead of a hybrid coil or bridge transformer feedback connection as in Fig. 1. In Fig. 2 the amplifying path is shown as comprising two tandem connected tubes 21 and 22. The usual plate current supply source B is indicated in the figure. Grid biasing resistors 23 and 24 with by-pass condensers 25 and 26 are also shown.

Output transformer 27 comprises a primary winding 28 connected to tube 22, a secondary winding 29 connected to line L , and a tertiary winding 30 connected to one end of a feedback path 32, the other end of which is connected to the bridge points 15 and 16 of the circuit of the input hybrid coil 5. A variable resistance 40 is shown as shunted across the feedback path, for example for gain control.

Fig. 3 shows an amplifier which is a modification of the amplifier of Fig. 1 having a feedback path 42 connected between the input transformer or hybrid coil 45 and the output transformer or hybrid coil 47 as in the case of the amplifier of Fig. 1, and having a second feedback path 43 connected between these transformers. If desired, a band elimination filter 50 may be connected in path 42 as shown, for purposes referred to hereinafter. A transmission control network 51, which may be, for example, structurally and functionally like the network 20 in path 2 of Fig. 1, but balanced to ground, is shown in path

43 of Fig. 3. If desired, a transformer 52 may be included in path 43. Then either line L' or line L, or both, can be unbalanced with respect to ground and still the longitudinal attenuation between the lines will be large. The transformer 52 may be for example a transformer of unity ratio or other suitable ratio, transmitting substantially without phase shift and with substantially uniform transmission efficiency a wide range of frequencies, as for instance a range from 1 kilocycle to 7000 kilocycles.

In Fig. 3 the low impedance winding 11 of the input transformer 45, and likewise the high impedance winding 13 of the output transformer 47, is shown in the symmetrical form, i. e., as balanced with respect to ground. The feedback path 43 and line L' are made conjugate by dividing the winding 11 into two parts N'A and N'B, which may be respectively referred to as the line winding and the feedback winding of the hybrid coil or transformer 45, and connecting across the dividing points 56 and 57 a balancing network 55 for balancing the impedance G_0 ; and similarly, the path 43 and line L are made conjugate by dividing the winding 13 into two parts N_A and N_B, which may be respectively referred to as the line winding and the feedback winding of the hybrid coil or transformer 47, and connecting across the dividing points 61 and 62 a balancing network 59 for balancing the impedance R_0 .

The networks 55 and 59 can be adjusted to adjust or set the values of impedances Z' and Z , respectively, in the general manner disclosed in the above-mentioned application filed of even date herewith. Such adjustment need not materially disturb conjugacy between the line L' and the feedback path 43, nor conjugacy between the line L and this feedback path; for negative or gain reducing feedback through path 43 tends to give such conjugacies regardless of whether such conjugacies would exist without feedback, and considerable amounts of such negative feedback give these conjugacies even when the impedances of the balancing networks are varied widely. As indicated above, the feedback through path 42 facilitates obtaining these conjugacies. Also as indicated above, the feedback through the feedback path 43 is applied to the amplifier through the transformers or hybrid coils 45 and 47, the transformers being included in the μ -circuit or forwardly transmitting portion of the feedback loop formed by the amplifying path and this feedback path; and consequently distortion introduced by the transformers is reduced by the feedback through the feedback path 43.

The feedback loop including feedback path 43 in Fig. 3 may be called the primary feedback loop or the $\mu_1\beta_1$ loop. The feedback loop formed by the amplifying path μ_2 , which is a part of μ_1 , and the feedback path 42, may be called the $\mu_2\beta_2$ loop, β_2 being all of the feedback loop not included in μ_2 . The amplification values μ_1 and μ_2 differ from each other by the sum of two factors. The first factor is the decibel difference in the step-up of the winding N'B and n'2 with respect to winding n'1. The second factor is the decibel difference in the step-down of the winding n1 with respect to the windings N_B and n2. The portion of μ_1 and μ_2 that are common to each other are designated as μ_0 and the remainder of both μ_1 and μ_2 and all of β_1 and β_2 are designated as β_0 . This division groups all the active elements of the feedback loops as in μ_0 and only passive elements as in β_0 . The two feedback paths afford better control of the overall feed-

back than would either one alone and thereby enable a greater amount of feedback to be obtained than could be obtained with either one alone. Further, by having both feedback paths contain the entire gain circuit of the amplifier and also include both the input and output coils, better control of the overall amplifier gain and impedance adjustments is obtained. By the use of two feedback paths each enclosing the entire amplifier and each by itself tending to produce by means of feedback the desired overall amplifier characteristics as to gain, input and output impedances, modulation, stability, etc., the controlling magnitude of feedback may be shifted from one path to the other as desired even within the transmission frequency range of the amplifier. Thereby better or more simple control can be obtained of the adjustments of the circuit brought about by means of feedback than could be obtained if only one feedback path were available for control of some of the adjustments obtained by means of feedback. Practical considerations at present ordinarily render it desirable to so limit the amount of feedback as to satisfy the condition that as long as the $\mu_0\beta_0$ loop has loop gain, the phase shift in transmission passing once around it shall not cross from the first to the fourth quadrant. The inclusion of all the non-linear elements of the circuit in a path that is common to all the feedback loops divides the amplifier circuit into μ_0 and β_0 paths as defined above; and this division of the elements renders a single test sufficient for the adjustment of the overall circuit for the maximum overall feedback possible under the condition just stated. As indicated above, an increase in total feedback over the feedback obtainable by one feedback path is obtainable by the introduction of another feedback path. With the use of the two feedback paths, the overall feedback may be shifted from one path to the other so that each path controls the total feedback over the band of its own frequency range. By having the active frequency range of each feedback path thus reduced it is possible to control its performance better and so provide by the sum of the two paths an overall feedback which gives a stable circuit but also provides greater feedback than was possible with only one path.

For a given circuit with only $\mu_1\beta_1$ active, β_1 can be adjusted so that any increase in the $\mu_1\beta_1$ transmission produces singing at the frequency where the $\mu_1\beta_1$ phase shift equals zero. The maximum feedback is thereby determined. Then let β_2 be made active and so adjusted that at the edges of the transmission band its transmission is small relative to that of β_1 and at the sing frequencies its transmission is large compared to that of β_1 . Under this condition the performance of circuit over the transmitted band is not materially altered. However, at the sing frequencies since the transmission of β_2 is much larger than β_1 the feedback is through it and not through the $\mu_1\beta_1$ path that caused the singing to exist. That is, at the potential sing frequencies of $\mu_1\beta_1$, the feedback is taken over by the β_2 path. The sing frequencies are thus dependent upon the $\mu_2\beta_2$ path not the $\mu_1\beta_1$ path. By means of this arrangement the β_1 transmission may be increased until it again becomes influential upon the $\mu_2\beta_2$ and produces singing. But this increased transmission produces a larger value of $\mu_1\beta_1$ in the transmitted band, which is increased feedback made possible by the introduction of another feedback path, the β_2 path. This exam-

ple is graphically illustrated by the curves of Fig. 4.

The control to produce this effect may be obtained by having the cut-off frequencies of a band elimination filter 50 lie between the transmission frequency band of the amplifier and the sing frequencies, as in the case of the band elimination filter in the internal feedback path of the multiple loop feedback amplifier of G. W. Barnes Patent 1,994,457, March 19, 1935. Thus, the pass band of filter 50 is such that path 42 does not feed back in the transmission frequency range of the amplifier but does give negative feedback at the lower and higher frequencies in the neighborhoods of the sing frequencies of the $\mu_1\beta_1$ loop, so feedback takes place around the $\mu_1\beta_1$ loop over the transmission frequency range but is transferred to the $\mu_2\beta_2$ loop in the regions of the sing frequencies. In Fig. 4 the abscissae represent frequency in cycles per second, and the ordinates represent loop gain, loop gain being decibel gain experienced by transmission in passing once around a feedback loop. Curve 71 in Fig. 4 may represent the decibel gain that would be experienced by transmission in passing once around the $\mu_1\beta_1$ loop of an amplifier circuit, such for example as that of Fig. 3, if there were no feedback around the inner loop, the sing frequencies then being, for example, as indicated at A and B in the figure. The circuit then has a maximum feedback F_1 , which exists in the amplifier adjustment for which the $\mu_1\beta_1$ loop gain, or decibel gain experienced by transmission in passing once around the $\mu_1\beta_1$ loop, becomes a loss at the sing frequencies A and B. Let the gain curve (or characteristic of loop gain versus frequency) for the $\mu_2\beta_2$ loop be as indicated by curve 72 in Fig. 4. The feedback through the $\mu_2\beta_2$ loop reduces the loop gain of the $\mu_1\beta_1$ loop so as to change the loop gain characteristic of the $\mu_1\beta_1$ loop from curve 71 to curve 71'. This characteristic exhibits a loss, indicated by C and D, shown as a 10-decibel loss, at the sing frequencies; so the loss in path 43 may be decreased by substantially that amount without causing the circuit to sing, and this correspondingly increases the loop gain of the $\mu_1\beta_1$ loop.

The feedback through path 42 can change not only the overall loop gain but also the phase shift of the overall loop, (i. e., the phase shift experienced by waves in passing once around the $\mu\beta$ loop), so as to increase the singing margin for a given amplifier gain. As the loop gain of the $\mu_2\beta_2$ loop increases the feedback through 42 changes the loop phase shift of the $\mu_1\beta_1$ loop an amount approximating the difference between the phase shift in β_2 and the phase shift in μ_2 , and this difference can be made of proper magnitude and sign to make this change shift the sing frequencies of the $\mu_1\beta_1$ loop to values that increase the margin against singing around the $\mu_1\beta_1$ loop.

There are many ways in which this division of control between the two—or more—feedback paths can be made. Also there are numerous effects in the overall feedback curve that results from different relations between two feedback paths that are transferring the controlling feedback from one path to the other. In general it is desired that the sum of the two feedbacks give a feedback gain curve (i. e., a loop gain curve) having a smooth slope with frequency. One way of getting this with slowly changing magnitudes in each of the two feedback paths under consideration is to have their phase shifts 120 degrees different. Either feedback path may control the

overall feedback at any desired frequency and still have the feedback improve the operation of the whole circuit as regards modulation reduction, transformer equalization and stabilization of amplifier gain against changes of tubes and variations of power supply for example. The two feedback paths are virtually in parallel to each other as regards their effects upon singing tendency in the amplifier. Each feedback path is effective in so feeding back through both the amplifier input transformer and the amplifier output transformer as to compensate for the transmission characteristics of these coils. The controlling magnitude of feedback may be changed from one feedback path to the other, either within the transmission frequency range or outside of it, and yet the feedback performance characteristics of the amplifier maintained, either circuit alone being effective to produce in one frequency range the feedback benefits produced by the other in a different frequency range. For example, the inner feedback path can take over the overall feedback and thereby prevent singing around the outer loop from being caused by excessive phase shift due, for instance, to transmission control elements or networks in path 43.

The coupling between the output of tube 21 and the input of tube 22 is shown in Fig. 3 as an interstage coupling circuit 79 comprising a transformer 80, resistors 81 and 82 and a by-pass condenser or direct current stopping condenser 85 whose capacity may be, for example, of the order of .1 microfarad. The resistor 81 is in series with the primary winding 83 of transformer 80 in the plate circuit of tube 21, and the resistor 82 is in series with the secondary winding 84 of the transformer 80 in the grid circuit of tube 22. The transformer may have a turns ratio of 1:1, for example, and the resistances 81 and 82 may be, for example, 10,000 ohms and 100,000 ohms, respectively. Without the resistances, the transformer would appear at low frequencies as a shunt inductance introducing -90 degrees phase shift and at high frequencies as a shunt capacity introducing +90 degrees phase shift. The resistances render the phase shift of the interstage coupling network substantially zero at low frequencies and reduce the phase shift to some 40 degrees or 50 degrees over a band of high frequencies. Parasitic shunt capacity tends to limit the band over which these resistances reduce the high frequency phase shift. Thus, the resistances reduce the phase shift some 50 degrees or 40 degrees at high frequencies at which, without such reduction of phase shift in the interstage coupling circuit, the system might sing; and the resistances also increase the singing margin at low frequencies.

The amount of feedback possible in a circuit containing two or more transformers may be greatly increased by the proper proportioning of the cut-off frequencies of the transformers used. In a feedback loop it is desirable to keep the phase shift around the loop from exceeding a finite value, usually ± 180 degrees from a mid-transmission band value, up to as high a frequency as possible above the transmission band and down to as low a frequency as possible below the transmission band. Furthermore, for a given phase shift cross-over frequency it is desirable to have had the gain change from its value at the edge of the transmission band by as large an amount as possible. The relation between the gain change and the phase change versus frequency is finite and expressed by a mathematic integral which states that the gain change possible is directly related

to the area under the phase change curve. From this consideration it is desirable to have the phase shift reach its limiting condition as soon after passing the mean as possible and then remain at that value to as high, or low, a frequency as possible before it "crosses over".

If this limiting condition is reached, then every octave the phase cross-over can be shifted up at the high frequencies or down at the low frequencies permits an increase of 12 decibels in gain-reducing feedback without causing instability.

Mathematically it makes no difference what units introduce the phase shift or whether it be all in one element or be divided between several. The loss curve will be identical in these different cases. Physically, however, it makes a great deal of difference in the complexity of the circuit required.

Physically each unit in the feedback loop has a finite ultimate phase shift and an associated gain change. The frequency at which the phase shift of a unit changes rapidly is a measure of its cut-off frequency and it may be shifted in the frequency spectrum by means of design, but relatively little control exists over the rate at which the phase shift changes when the point of phase inflection is reached. For this reason the phase shift in the feedback loop tends to increase abruptly at specific frequencies (at the frequencies of abrupt phase increase of the several elements in the circuit). Since the sum of the ultimate phase shifts introduced by all the elements in the feedback loop far exceeds that required to produce singing, in order to give a stable circuit the several elements should have their cut-off frequencies so staggered that over as wide a frequency range as possible the loop phase shift does not exceed the working limit of ± 180 degrees previously referred to. Stated differently the cut-off frequencies of the several elements should be properly staggered to provide the conditions for the most possible feed-back. The amount of staggering desirable is directly related to the design of transformers used, and should be adjusted so as to approach as closely as possible the working limit of ± 180 degrees.

In this design the phase shift through the coupling transformer 80 reaches its maximum value as rapidly as possible above and below the mid-band frequency. Likewise the phase shift through the input coil 45 is realized as near mid-band as other considerations permit. In order to prevent the phase shift from these two elements alone from exceeding ± 180 degrees at frequencies relatively close to the transmission band and so permitting very little feedback, the interstage coupling unit is so designed that the sum of its phase shift plus that of the input coil approaches as nearly as possible, but does not exceed, ± 180 degrees, over as wide a frequency band as control of the design permits.

The output coil 47 and the coil 52 in the feedback path 43 are constructed so that their phase shift is introduced only after departure from the mid-band frequency as much as possible. Thus the change in loop phase shift from the mid-band value is made as near the maximum permissible amount as close to the mid-band frequency as possible by the interstage coupling coil and the input coil, and the output coil and the feedback coil introduce as little as possible. By this means the interstage coil and input coil produce as much gain change as possible in the feedback loop before the phase shift limit is ex-

ceeded due to the added phase shift introduced by the output coil and the feedback coil.

This adjustment of characteristics may be stated by saying that the cut-off frequencies of the several units are adjusted relative to one another. In this circuit the cut-offs of the several units are approximately as follows: the input coil, 5 kilocycles and 15 kilocycles; the output coil 1 kilocycle and 80 kilocycles; the feedback coil 1 kilocycle and 3000 kilocycles; and the interstage coil 80 anti-resonant at 12 kilocycles.

What is claimed is:

1. An amplifier having an amplifying path and a feedback path therefor feeding back waves in gain-reducing phase, a balancing circuit for said amplifying path, a wave transmission circuit forming a load circuit for said amplifier, a transformer, said amplifying path including an anode, a cathode and an anode-cathode space discharge path, said transformer having a two-part winding with both parts and said space discharge path and said balancing circuit all in series, said transformer having a second winding, means connecting said second winding in said transmission circuit, and means connecting said feedback path to said cathode and the division point of the two-part winding.

2. An amplifier comprising an amplifying path and a feedback path therefor feeding back waves in gain-reducing phase, a balancing path for said amplifying path, a wave transmission path forming a load circuit for said amplifier, means comprising a transformer to associate the amplifier output with said balancing path and said wave transmission path for transmission from said amplifier to said load circuit, said amplifying path comprising an anode, a cathode and an anode-cathode space discharge path, said transformer having a two-part winding with both parts and said space discharge path and said balancing path all in series, said transformer having a second winding in a third of said four first-mentioned paths, and means for connecting the remaining one of said four paths to said cathode and the division point of the divided winding.

3. A wave translating system comprising an amplifying path and a feedback path therefor feeding waves back in gain-reducing phase, said amplifying path including an electric space discharge device having an anode, a cathode and a discharge control electrode, a wave transmission circuit for association with said amplifying path, a two-terminal impedance, a hybrid coil with effectively three transformer windings connected one between said control electrode and one side of said feedback path, a second between said one side of said feedback path and one terminal of said impedance, and a third in said circuit, and means connecting the other side of said feedback path to said cathode and to the other terminal of said impedance, the value of said impedance substantially differing from that which would be required for conjugacy between said feedback path and said circuit in the absence of feedback through said feedback path.

4. A wave translating system comprising an amplifying path and a feedback path therefor feeding waves back in gain-reducing phase, a balancing circuit for said amplifying path, a wave transmission circuit for association with the output end of said amplifying path to transmit waves received from said path, a circuit connecting said amplifying path and said balancing circuit in series with each other, a trans-

former having a divided winding in series in said circuit and an inductively related winding in said wave transmission circuit, said feedback path having one terminal at one side of said amplifying path and one side of said balancing path and another terminal at the division point of said divided winding, the impedance of said balancing circuit substantially differing from the value that would be required for conjugacy between said feedback path and said transmission circuit in the absence of feedback through said feedback path, and said feedback path producing sufficient feedback to render the impedance of said inductively related winding viewed from said transmission circuit substantially independent of variation in the impedance of said feedback path attached to said terminals.

5. A wave translating system comprising an amplifying path and a feedback path therefor, a wave source for connection to one end of said amplifying path, a load device for connection to the other end of said amplifying path, two balancing impedances, a circuit connecting one end of said amplifying path and one of said balancing impedances in series with each other, a transformer having a divided winding in series in said circuit and an inductively related winding in series with said source, a circuit connecting said other end of said amplifying path and said other balancing impedance in series with each other, and a second transformer having a divided winding in series in said latter circuit, said feedback circuit connecting the dividing point of one of said divided windings to the dividing point of said other divided winding.

6. A wave amplifying system comprising an amplifying path, two feedback paths therefor, a circuit for connection to said amplifying path, and means comprising a four-winding transformer for connecting said amplifying path for transmission to said circuit and to each of said feedback paths and rendering said feedback paths conjugate to each other and to said circuit.

7. A wave amplifying system comprising an amplifying path, two feedback paths therefor, a circuit for connection to said amplifying path, two impedances, and a four-winding transformer connecting said amplifying path to said circuit and to each of said feedback paths, with said feedback paths conjugate to each other and to said circuit, and with one of said feedback paths conjugate to one of said impedances and with said amplifying path conjugate to said other impedance.

8. A wave amplifying system comprising an amplifying path with two feedback paths therefor, a circuit for association with said amplifying path, and means for connecting said amplifying path to said feedback paths and said circuit, said means comprising a transformer and two impedances, said transformer having one winding connecting said amplifying path and one of said feedback paths, a second winding connecting said one feedback path and one of said impedances, a third winding connecting said circuit and said other impedance, and a fourth

winding connecting the latter impedance and said other feedback path.

9. A wave translating system comprising an amplifying path with two conjugate feedback paths each feeding waves from the output end of said amplifying path to its input end, a wave transmission circuit, a transformer having a high impedance winding connected to said amplifying path and one of said feedback paths and having a low impedance winding connected to said circuit and to said other feedback path, and frequency selective means in said one feedback path for suppressing transmission of waves to be amplified in said amplifying path.

10. An electric wave amplifier having an amplifying path with two feedback paths therefor, a wave transmission circuit, a transformer and two impedances for rendering each of said feedback paths conjugate to the other and to said circuit, and frequency selective means in one of said feedback paths for preventing feedback therethrough of the waves to be amplified.

11. A thermionic amplifier comprising an amplifying path forming a main speech path provided with a negative feedback path from the output end to the input end of the main speech path for the reduction of non-linear distortion, and coupling devices in the main speech path and the feedback path having different cut-off frequencies whereby the degree of negative feedback consistent with stability is made greater than would be possible with coupling devices having similar characteristics.

12. A cascade-connected transformer coupled thermionic amplifier comprising a main transmission path including wave amplifying devices, a feedback path therefor feeding back waves in gain-reducing phase for reducing non-linear distortion, transformer means in said main transmission path, and a transformer in said feedback path passing a substantially wider range of frequencies than said transformer means in said main transmission path.

13. A cascade-connected transformer coupled thermionic amplifier comprising an amplifying path with a feedback path therefor extending from the output end to the input end thereof and forming therewith a feedback loop feeding back waves in gain-reducing phase for reducing non-linear distortion, and coupling devices in the feedback loop having different cut-off frequencies whereby the degree of negative feedback consistent with stability is made greater than would be possible with coupling devices having similar characteristics.

14. A cascade-connected thermionic amplifier with a feedback path therefor feeding back waves in gain-reducing phase for reducing non-linear distortion, and a plurality of coupling transformers included in the feedback loop, one of said transformers contributing the major portion of the phase shift and gain change of the feedback loop propagation at each end of the frequency range.

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