Aug. 20, 1935. H. S. BLACK 2,011,566

WAVE TRANSLATION SYSTEM

Filed Dec. 29, 1932 2 Sheets-Sheet 1

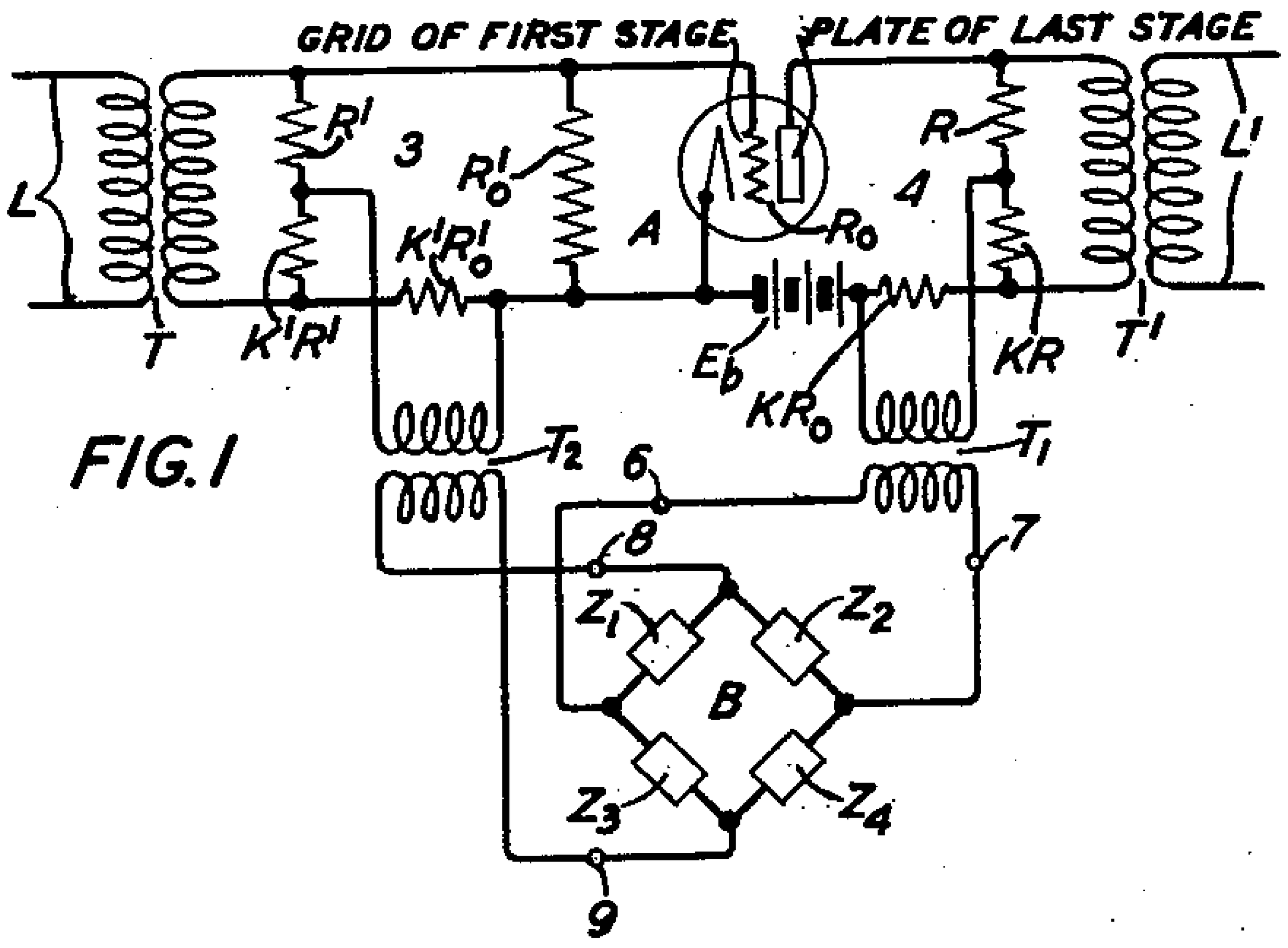


FIG. 1

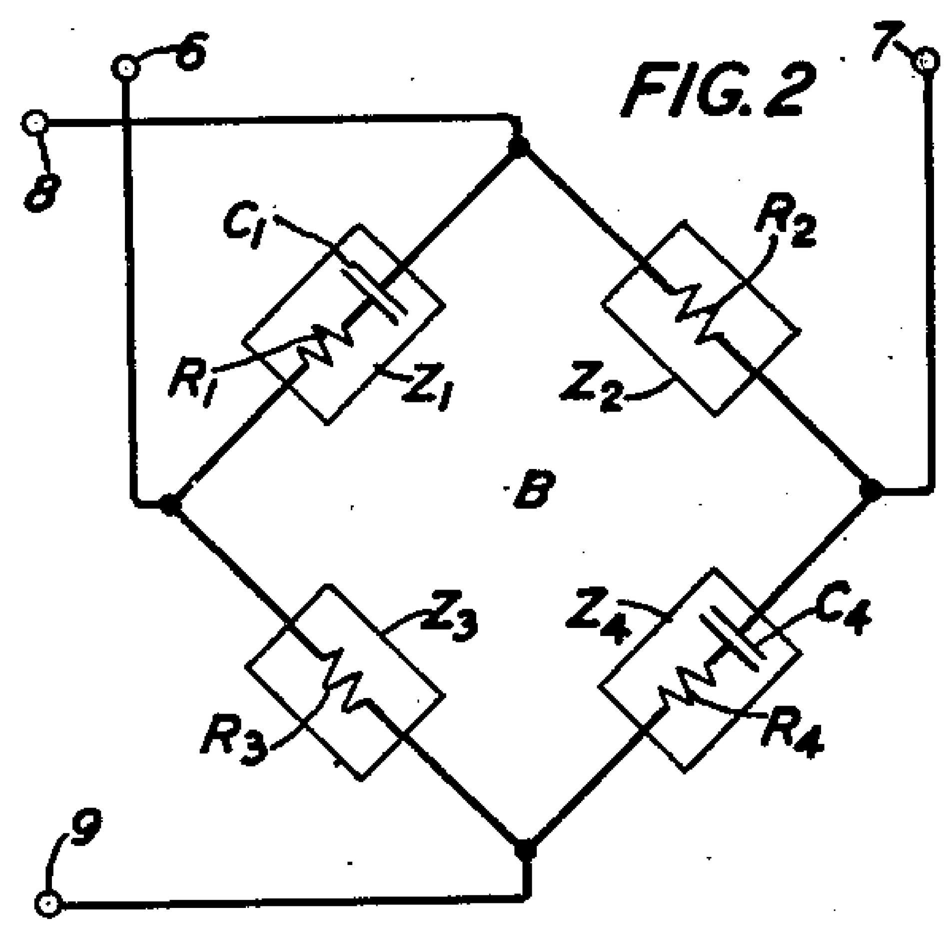
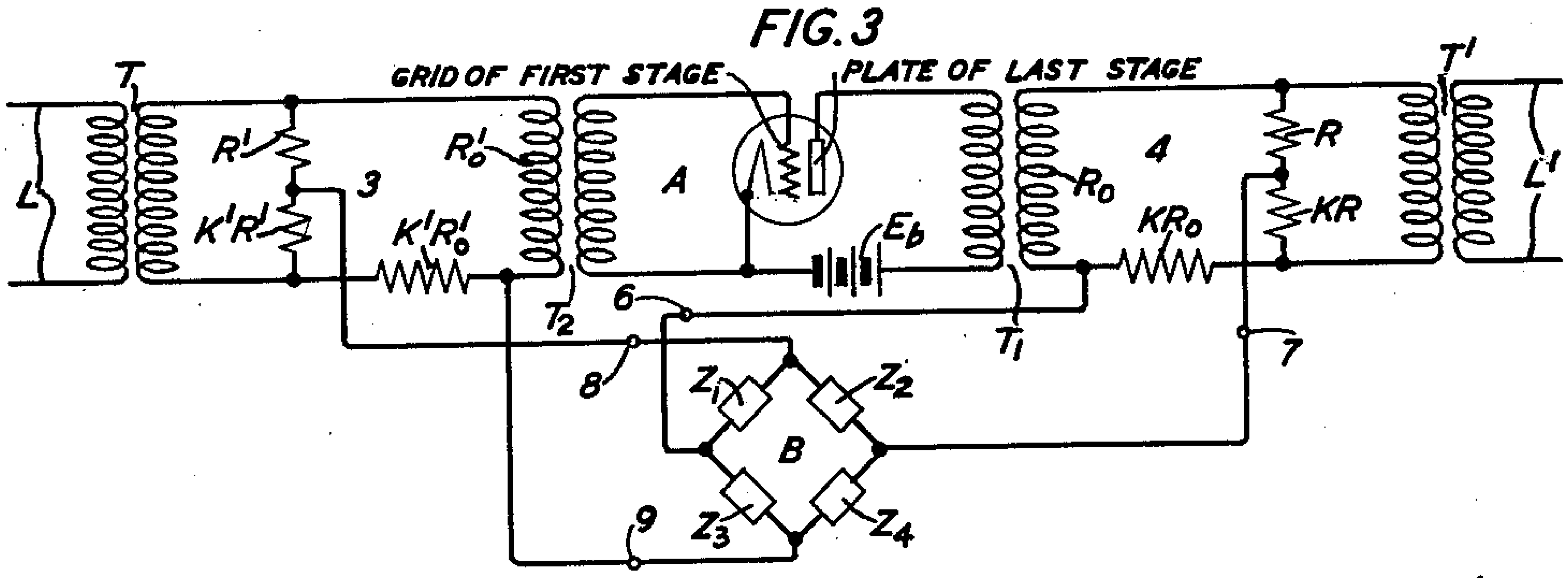


FIG. 2

FIG. 3



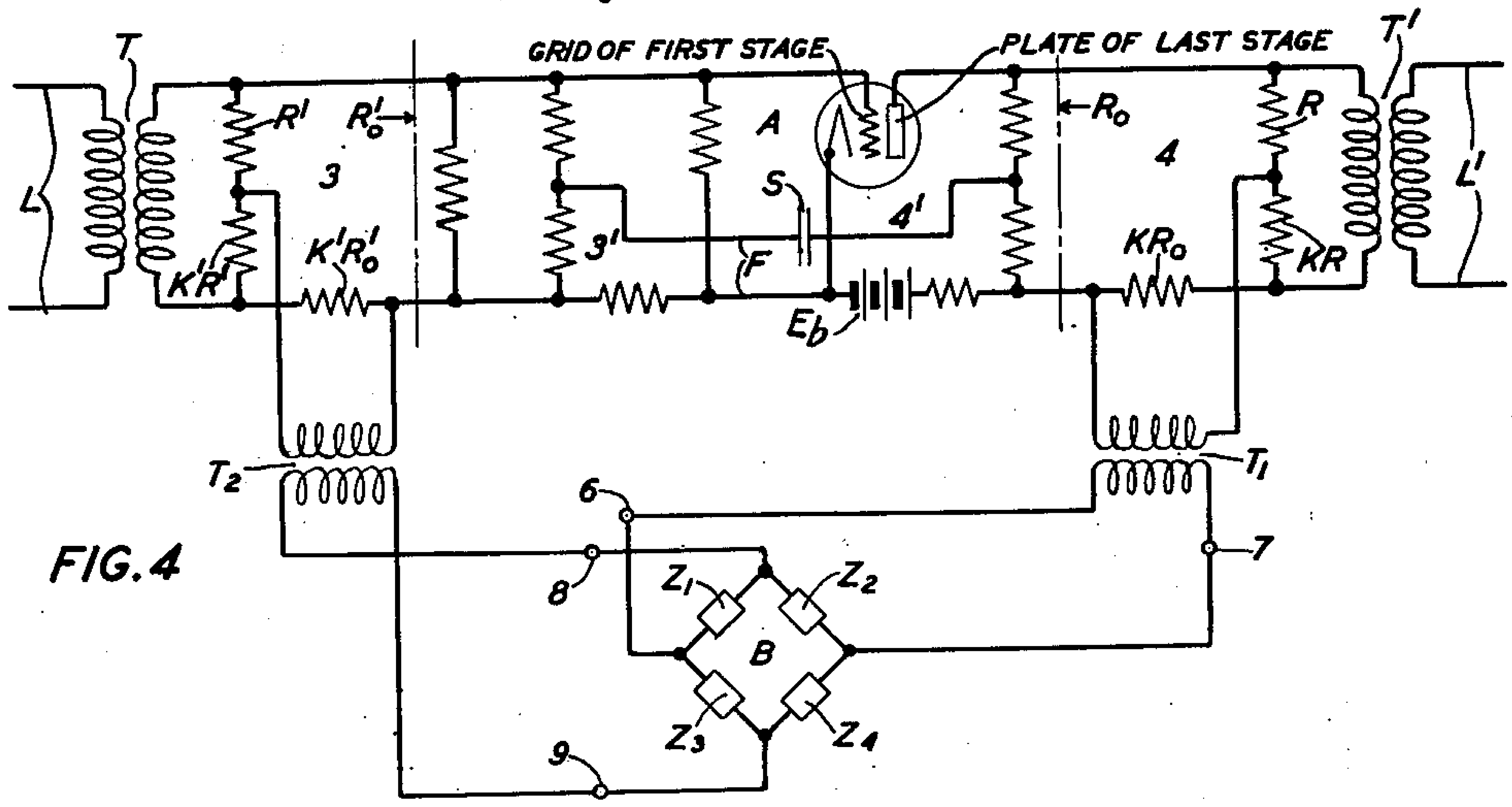


FIG. 4

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FIG. 5

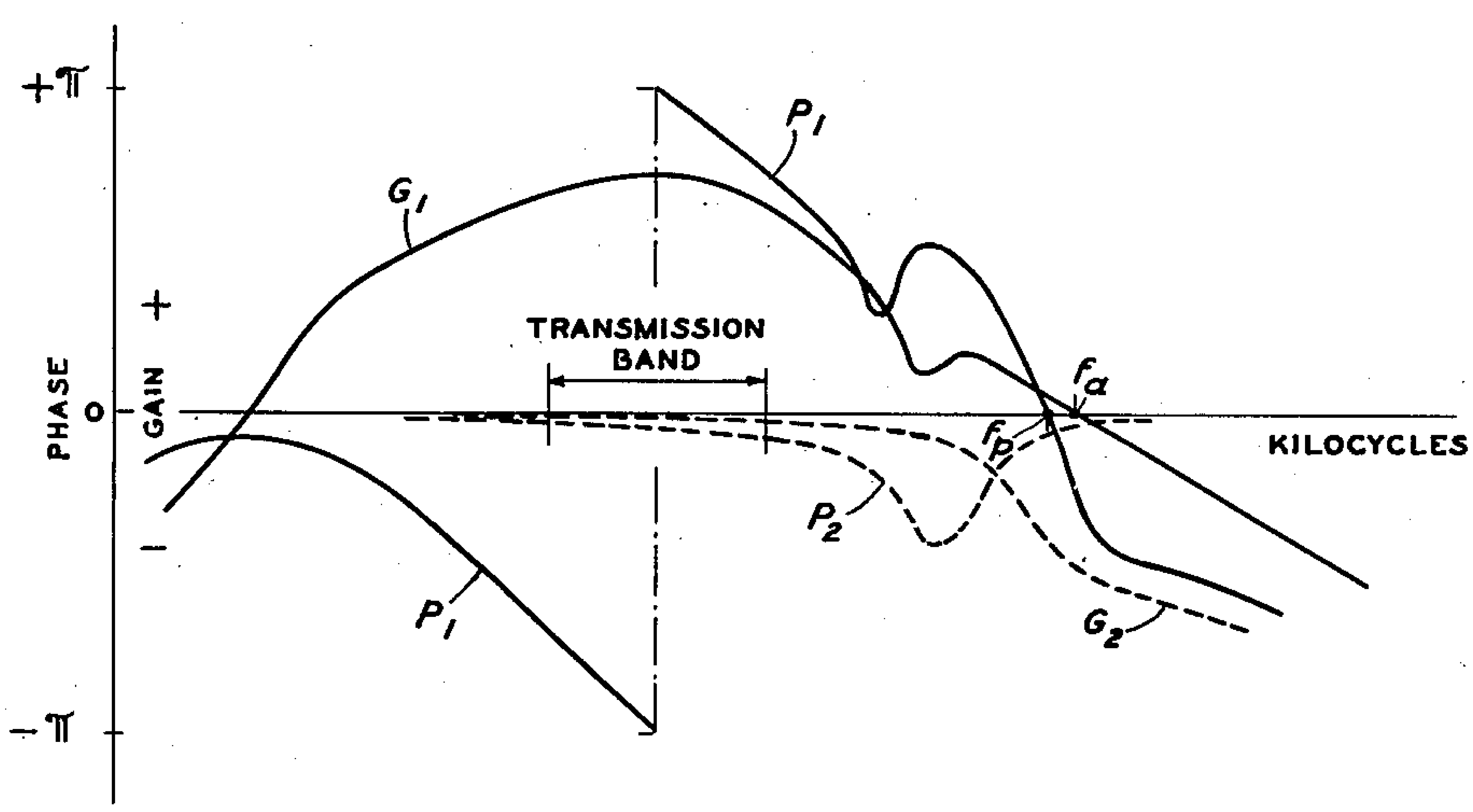
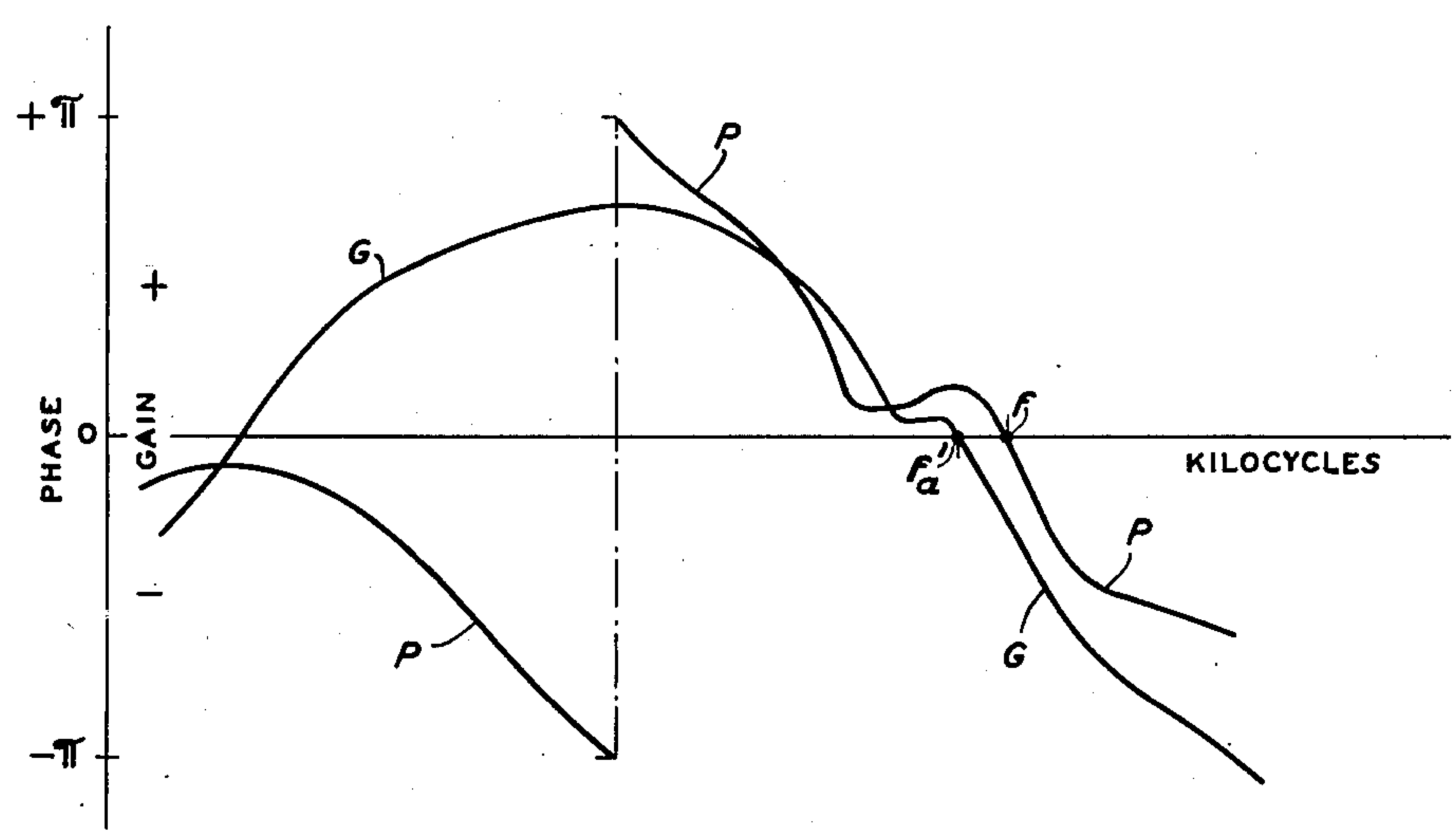


FIG. 6



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UNITED STATES PATENT OFFICE

2,011,566

WAVE TRANSLATION SYSTEM

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Application December 29, 1932, Serial No. 649,252

18 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.

Objects of the invention are to control amplitude and phase of waves in such systems, and it is especially an object of the invention to so control feedback in such systems as to reduce singing tendency in the systems, as for example to reduce singing tendency in amplifiers that feed back modulation or distortion components for reducing distortion, or feed back fundamental components for increasing stability, or both. Such amplifiers are disclosed, for example in British Patent 317,005.

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 from the output to the input is designated μ and is what the voltage on the grid of the first tube must be multiplied by to obtain the phase and magnitude of the total resulting voltage in the plate circuit of the last tube. Amplification ratio is the absolute 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 my copending application Serial No. 606,871, filed April 22, 1932, for Wave translation system, of which this application is a continuation in part 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 negative 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 the general type in which 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. That type of amplifier is disclosed for example in the above mentioned copending application and in the above mentioned British patent.

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. In practice, when the loop gain (i. e., the decibel gain for a single trip around the loop) is large for the frequencies of the utilized frequency range, it is greater than zero for some higher 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.) Moreover, passive networks introduced in the loop to contribute a component of loop attenuation increasing with frequency ordinarily introduce a component of loop phase shift that tends to lower the frequency, and raise the gain, at which the loop phase shift reaches a given multiple of 360°. To avoid the singing condition, it is desirable to control the loop phase shift and the loop gain carefully with respect to the entire frequency spectrum. (Such control is desirable also for other reasons, as for example to prevent loop phase shift from causing increase in the gain of the amplifier, which increase may be undesirable because accompanied by a corresponding increase in the modulation products. This increase in gain may become a limiting factor determining the permissible loop phase shift at high frequencies where it becomes difficult to obtain sufficient feedback. At other frequencies it is usually not a limiting factor. For example, assuming the amplifier does not sing, the amplifier gain change produced by feedback will be within 1 decibel of the gain around the feedback loop regardless of phase shift if the gain around the loop exceeds 20 decibels. Further, the feedback does not increase the amplifier gain if the loop gain exceeds 6 decibels.) If the value of the loop phase shift were maintained at ±180° 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 nor touch the zero phase shift axis in the frequency range of loop gain. (It is not be inferred that this requirement is always essential for freedom from singing. A criterion for such freedom is given by Nyquists'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 interelectrode 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° 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 phase shifts around the closed loop may become large. For example, they may become large at frequencies well above the utilized range because of shunt capacitance, for instance, tube and wiring capacities. The singing tendency may become particularly troublesome when the amplifier is called upon to transmit wide frequency bands extending to very high frequencies, for example.

In its specific aspect mentioned above, the invention is a negative feedback amplifier with a bridge network in the closed feedback loop, for instance in the feedback path, the bridge having its input in one of its diagonals and its output in the other diagonal and being adjusted to reduce singing tendency by producing large attenuation of waves, in their passage once around the closed feedback loop, at only frequencies outside of the utilized range.

For example, the loss introduced by the bridge may be made to be low over the utilized frequency range and increase with frequency above that range, so that the loop gain decreases above that range and becomes less than zero before the loop phase shift frequency characteristic crosses or reaches the zero axis of loop phase shift.

As disclosed for example in the above mentioned copending application and described hereinafter, a feedback amplifier or circuit can be provided with an input bridge for reducing reaction between the incoming circuit and the feedback path, or with an output bridge for reducing reaction between a load circuit and the feedback path, or with both.

As indicated above, loop gain and loop phase shift present important limitations in operation of feedback amplifiers, especially the loop gain and loop phase shift at high frequencies in operation of wide band negative feedback amplifiers for reducing modulation or distortion by feedback action.

An object of the invention is to control such loop gain and loop phase shift.

It is also an object of the invention to reduce singing tendency or to increase the distortion suppression obtainable in such amplifiers, or both.

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

In the accompanying drawings,

Fig. 1 is a circuit diagram of a vacuum tube amplifier embodying a form of the invention, with a bridge located in a feedback path and having arms shown as generalized impedances;

Fig. 2 is a circuit diagram showing an example of a specific form which the bridge may have;

Figs. 3 and 4 show modifications of the amplifier of Fig. 1, and Figs. 5 and 6 show curves facilitating explanation of the invention.

In Fig. 1 a negative feedback amplifier amplifies waves received by input transformer T from line or circuit L and transmits the amplified waves through output transformer T' to line or circuit L'. The amplifier comprises a forwardly transmitting path A including a vacuum tube or any number of vacuum tube stages in tandem, and comprises a feedback path including a bridge network B. Bridge B has input diagonal across terminals 6 and 7 and its output diagonal across terminals 8 and 9, and has its ratio arms shown as generalized impedances Z_1, Z_2, Z_3 and Z_4. An amplifier input bridge network 3 renders the feedback path and the circuit conjugate and an amplifier output bridge 4 renders the feedback path and the circuit L' conjugate, in the manner disclosed, for example, in the above mentioned copending application. The ratio arms of bridge 4 are resistances or impedances R_o, KR_o, KR and R. The ratio arms of bridge 3 are resistances or impedance R'_o, $K'R'_o$, K'R' and R'. The tubes of path A may be resistance coupled, for example, or they may be coupled, for example, by networks of substantially zero phase shift as disclosed in Nyquist Patent 1,894,322, Jan. 17, 1933. Excepting plate current supply battery E_b, only the alternating current circuits of the amplifiers are shown, the direct current energizing circuits or other circuits for energizing the amplifier or conditioning it for operation being omitted for the sake of simplicity as they can readily be supplied by those skilled in the art.

Transformers T_1 and T_2 in the diagonals of bridge B prevent short-circuiting of one of the arms of the bridge notwithstanding the fact that the cathode structure of the tube is common to the output and input circuits of the tubes and consequently common to the input and output diagonals of the bridge if the bridge is so connected in circuit that bridge balance prevents feedback outside of the utilized frequency range. Either transformer can be omitted and the other will still accomplish this function.

The amplifier may be of the general type referred to above as disclosed in the above mentioned copending application, Serial No. 606,871, in which, over the range of transmitted frequencies, loop gain $>>1$ and in which waves, including fundamental and distortion waves of the range of transmitted frequencies, 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. If desired, either or both of the bridges **3** and **4** can be omitted; and regardless of whether or not such bridges are used, the transformers T and T′ can be included in the closed feedback loop, with consequent advantages brought out in the above mentioned copending application, Serial No. 606,871.

Fig. 2 shows a form of the bridge B that is useful in the amplifier of Fig. 1, for example, for introducing in the feedback path or in the closed feedback loop a large loss at only frequencies outside of the utilized range. In this form of the bridge the arm Z_1 is a resistance R_1 and a capacity C_1 in series, the arm Z_4 is a resistance R_4 and a capacity C_4 in series, and the arms Z_2 and Z_3 are resistances R_2 and R_3, respectively. These various resistances and capacities have values of small magnitudes such that at the frequencies of the utilized frequency range (for example, the range from four kilocycles to forty kilocycles) the loss in the bridge is too small to materially affect operation of the circuit (current passing freely through R_2 and R_3, but not through C_1 nor C_4), and at higher frequencies (for example, the range from 200 kilocycles to 3,000 kilocycles, in which the singing tendency may be troublesome) the reactances of condensers C_1 and C_4 are small and the bridge is substantially balanced and presents large loss to transmission from the terminals **6** and **7** to terminals **8** and **9** without objectionably shifting the phase and thereby reduces the singing tendency.

Figs. 5 and 6 show curves of a typical amplifier such as that of Fig. 1. In each of these two figures the abscissae are frequencies, in kilocycles, and the ordinates are phase angles and gains. In Fig. 5 curves G_1 and P_1 respectively show the loop gain and the angle of the loop phase shift for the amplifier feedback loop) when the bridge B is omitted; and in Fig. 6, curves G and P respectively show the loop gain and the angle of the loop phase shift for the amplifier with the bridge B in circuit. In Fig. 5, the curves G_2 and P_2 respectively show the insertion gain and phase shift introduced by the bridge B. Thus, curve P of Fig. 6 is obtained by adding curves P_1 and P_2 of Fig. 5; and curve G of Fig. 6 is obtained by adding curves G_1 and G_2 of Fig. 5. The component of loop gain produced by bridge B is a negative gain, i. e. a loss. The transmission band, or utilized frequency range of the amplifier may be, for example, as indicated by legend in Fig. 5.

Curve P_1 shows the loop phase shift (without B) as a small negative angle (in the fourth quadrant) at a frequency below the utilized frequency range. As the frequency increases from that value to a frequency in the utilized range the curve shows the loop phase shift increasing its negative value until it becomes 180°. Then as the frequency continues to increase the curve shows the loop phase shift decreasing from 180° to angles in the first quadrant. At still higher frequencies the curve shows the loop phase shift approaching zero, which it reaches at frequency f_p, for example, a frequency well above the utilized frequency range. The frequency f_p is therefore a potential singing freguency, i. e., a frequency at which the amplifier without B may sing around the loop since curve G_1 shows the loop gain greater than zero at that frequency of zero loop phase shift. However, the bridge B prevents the amplifier from singing; for with the bridge B adjusted as indicated above, the bridge can be made to contribute to the amplifier loop gain and loop phase shift such components (shown by curves G_2 and P_2) as to lower the frequency at which the loop gain reaches zero (and changes from a positive value to a negative value or a loss) from the frequency value shown at f_a in Fig. 5 to the frequency value shown at f'_a in Fig. 6, and at the same time to lower the frequency at which the loop phase shift reaches zero (and changes sign) only an amount so small as to be unobjectionable, e. g. from the frequency value shown at f_p in Fig. 5 to the frequency value shown at f in Fig. 6. Thus, with the bridge B functioning. as frequency increases, above the utilized frequency range, the loop gain becomes a loss before the loop phase shift reaches zero, and consequently the singing tendency of the amplifier is reduced or the singing margin increased, and the loop gain permissible in the utilized frequency range is increased, so increased distortion suppression and amplifier gain and gain stability can be obtained.

Fig. 3 shows an amplifier circuit like that of Fig. 1 except that the transformers T_1 and T_2 are in the forwardly transmitting portion of the amplifier instead of in the feedback path. As in the case of Fig. 1, either transformer may be omitted. The form of the bridge B in Fig. 3 may be that shown in Fig. 2, for example.

Fig. 4 shows an amplifier circuit like that of Fig. 1 except that there has been added an input bridge **3′** between the input bridge **3** and the tubes A, an output bridge **4′** between the tubes A and the output bridge **4**, and a feedback path F (including stopping condenser S) rendered conjugate to transformers T_1 and T′ by bridge **4′** and to transformers T_2 and T by bridge **3′** so that the amplifier effects repetition of the feedback process in the general manner described in connection with Figs. 38 and 73 of my above mentioned copending application, Serial No. 606,871. The bridge B in Fig. 4 may be of the form shown in Fig. 2, for example, and may be regarded as corresponding to one of the networks **571**, **572** and 573 in the feedback path 563 of Fig. 73 just mentioned, being in the feedback path through which the second feedback process takes place, the first feedback process taking place in the inner closed feedback loop which comprises the tubes A, feedback path F and bridges 3' and 4'.

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

What is claimed is:

1. A wave translating system comprising a closed feedback loop, a source of gain included in said loop, means included in said loop for producing negative feedback in said source of gain in the utilized frequency range, said loop tending to sing at a frequency outside of the utilized frequency range, and means in said loop for reducing the singing tendency of the loop outside of the utilized frequency range while keeping unchanged the loop gain at a given frequency of the utilized frequency range.

2. A wave translating system comprising a closed feedback loop, an active transducer included in said loop, means included in said loop for producing negative feedback in said transducer of waves in the utilized frequency range, said loop tending to sing at a frequency outside of the utilized frequency range, and frequency selective means in said loop for reducing the singing tendency of the loop outside of the utilized frequency range while keeping unchanged the loop gain at a given frequency of the utilized frequency range.

3. A wave translating system comprising a closed feedback loop, a source of gain included in said loop, means included in said loop for producing negative feedback in said source of gain in the utilized frequency range, said loop tending to sing at a frequency outside of the utilized frequency range, and attenuating means in said loop for reducing the singing tendency of the loop outside of the utilized frequency range while keeping unchanged the loop gain at a given frequency of the utilized frequency range.

4. A wave translating system comprising a closed feedback loop, an active transducer included in said loop, an input circuit and an output circuit connected to said transducer, means included in said loop for producing negative feedback in said transducer of waves in the utilized frequency range, a feedback path for feeding waves from the output of said transducer to its input included in said means, and means in said path for reducing the maximum loop gain for the frequencies at which the loop phase shift is zero and multiples of 360° more than the loop gain for a given frequency in the utilized frequency range at which the reduction of loop gain produced by said last mentioned means is the maximum for said range.

5. A wave translating system comprising a closed feedback loop, an active transducer included in said loop, an input circuit and an output circuit connected to said transducer, means included in said loop for producing negative feedback in said transducer of waves in the utilized frequency range, a feedback path for feeding waves from the output of said transducer to its input included in said means, and attenuating means in said path having greater loss at all frequencies at which the loop phase shift is zero and multiples of 360° than at a frequency of the utilized frequency range and having loss in the neighborhood of a frequency of zero loop phase shift exceeding its greatest loss in the utilized frequency range.

6. A wave translating system comprising a closed feedback loop, an active transducer included in said loop, means included in said loop for producing negative feedback in said transducer of waves in the utilized frequency range, and attenuating means in said loop having losses that are large at frequencies outside of the utilized frequency range compared to its losses within the utilized frequency range and that increase the minimum departure of the loop gain from zero and greater values for the frequencies at which the loop phase shift is zero and multiples of 360°, said attenuating means having its attenuation at all frequencies between the upper limit of the utilized frequency range and a frequency of zero loop phase shift exceed its highest attenuation in the utilized frequency range.

7. A wave translating system comprising a closed feedback loop, a source of gain included in said loop, means included in said loop for producing negative feedback in said source of gain of fundamental waves in the utilized frequency range, said loop tending to sing at a frequency outside of the utilized frequency range, and means in said loop for reducing the singing tendency of the loop outside of the utilized frequency range while keeping unchanged the loop gain at the maximum frequency of the utilized frequency range.

8. A wave translating system comprising a closed feedback loop, a source of gain included in said loop, means included in said loop for producing negative feedback in said source of gain in the utilized frequency range, said loop tending to sing at a frequency outside of the utilized frequency range, and means in said loop for reducing the singing tendency of the loop outside of the utilized frequency range while keeping unchanged the minimum loop gain in the utilized frequency range.

9. A wave translating system comprising a closed feedback loop, a source of gain included in said loop, means included in said loop for producing negative feedback in said source of gain in the utilized frequency range, said loop tending to sing at a frequency outside of the utilized frequency range, and means in said loop for reducing the singing tendency of the loop outside of the utilized frequency range while keeping unchanged the loop gain-frequency characteristic over the utilized frequency range.

10. A wave translating system comprising a closed feedback loop, an active transducer included in said loop, means included in said loop for producing negative feedback in said transducer of waves in the utilized frequency range, said loop tending to sing at a frequency outside of the utilized frequency range, and frequency selective attenuating means in said loop for reducing the singing tendency of the loop outside of the utilized frequency range while keeping unchanged the loop gain at a given frequency of the utilized frequency range.

11. A wave translating system comprising a closed feedback loop, an active transducer included in said loop, an input circuit and an output circuit connected to said transducer, means included in said loop for producing negative feedback in said transducer of waves in the utilized frequency range, a feedback path for feeding waves from the output of said transducer to its input included in said means, said loop tending to sing at a frequency outside of the utilized fre-

quency range, and frequency selective means included in said path for reducing the singing tendency of the loop outside of the utilized frequency range.

12. A wave translating system comprising a closed feedback loop, an active transducer included in said loop, an input circuit and an output circuit connected to said transducer, means included in said loop for producing negative feedback in said transducer of waves in the utilized frequency range, a feedback path for feeding waves from the output of said transducer to its input included in said means, and means in said path for reducing the maximum loop gain for the frequencies for which the loop phase shift is zero and multiples of 360° more than the loop gain for the frequency of minimum loop gain in the utilized frequency range.

13. A wave translating system comprising a closed feedback loop, a wave transducer having a gain included in said loop, an incoming circuit and an outgoing circuit connected to said transducer, means included in said loop for producing negative feedback in said transducer of waves in the utilized frequency range, a feedback path for feeding waves from the output of said transducer to its input included in said means, and means included in said path for reducing the maximum loop gain for the frequencies at which the loop phase shift is zero and multiples of 360° more than the loop gain for a given frequency in the utilized frequency range at which the reduction of loop gain produced by said last-mentioned means is the maximum for said range.

14. A wave translating system comprising a closed feedback loop, an active transducer included in said loop, an input circuit and an output circuit connected to said transducer, means included in said loop for producing negative feedback in said transducer of waves in the utilized frequency range, a feedback path for feeding waves from the output of said transducer to its input included in said means, and attenuating means in said path having greater loss at all frequencies at which the loop phase shift is zero and multiples of 360° than its greatest loss in the utilized frequency range.

15. A wave translating system comprising a closed feedback loop, an active transducer included in said loop, an incoming circuit and an outgoing circuit connected to said transducer, means included in said loop for producing negative feedback in said transducer of waves in the utilized frequency range, a feedback path for feeding waves from the output of said transducer to its input included in said means, and attenuating means in said path having greater loss at all frequencies at which the loop phase shift is zero and multiples of 360° than at the highest frequency of the utilized frequency range.

16. A wave translating system comprising a closed feedback loop, an active transducer included in said loop, an incoming circuit and an outgoing circuit connected to said transducer, means included in said loop for producing negative feedback in said transducer of waves in the utilized frequency range, a feedback path for feeding waves from the output of said transducer to its input included in said means, and attenuating means included in said path having losses that are large at frequencies outside of the utilized frequency range compared to its losses within the utilized frequency range and that increase the loop loss for the frequencies at which the loop phase shift is zero and multiples of 360°, said attenuating means having its attenuation at a frequency of zero loop phase shift exceed its highest attenuation in the utilized frequency range.

17. A wave transmission system comprising a closed feedback loop, an active transducer included in said loop, and means included in said loop for so feeding waves in the utilized frequency range from the output of the transducer back to its input as to reduce their power at the output, said means comprising a bridge network adapted to produce in waves in their passage once around the loop, a loss whose values for frequencies outside of the utilized frequency range are large compared to its values for the frequencies within that range and whose value for a frequency of zero loop phase shift above the utilized frequency range exceeds its largest value in that range.

18. A wave translating system comprising an amplifier with negative feedback of waves in the utilized frequency range, said amplifier comprising a bridge network unbalanced at one frequency and substantially balanced at another frequency, one diagonal of the bridge being coupled to the output circuit of said amplifier and the other diagonal being back-coupled to the input circuit of the amplifier, whereby the back-coupling through the bridge between the input and output circuits of the amplifier is greater for said one frequency than for said other frequency.

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