

July 20, 1943.

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2,324,815

STABILIZED FEEDBACK SYSTEM

Filed Feb. 28, 1942

2 Sheets-Sheet 1

FIG. 1

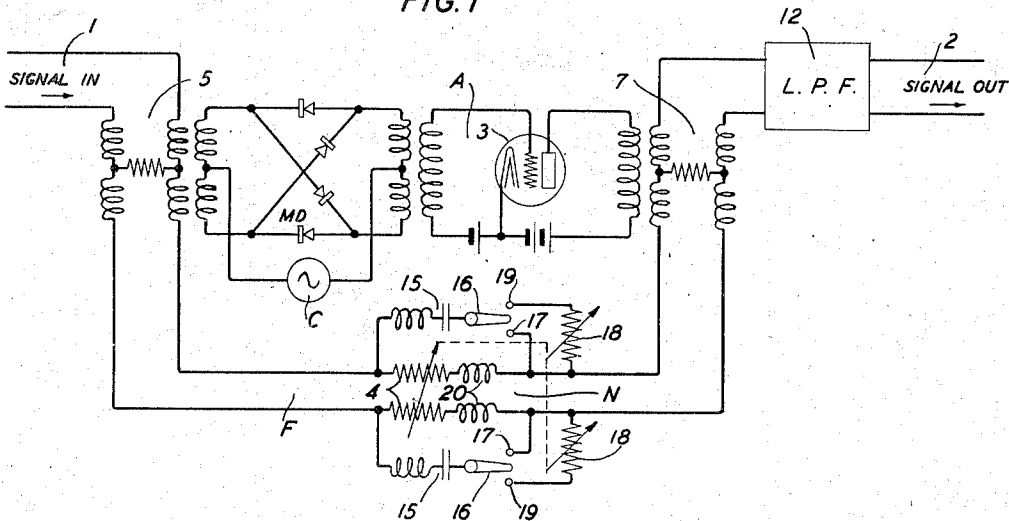
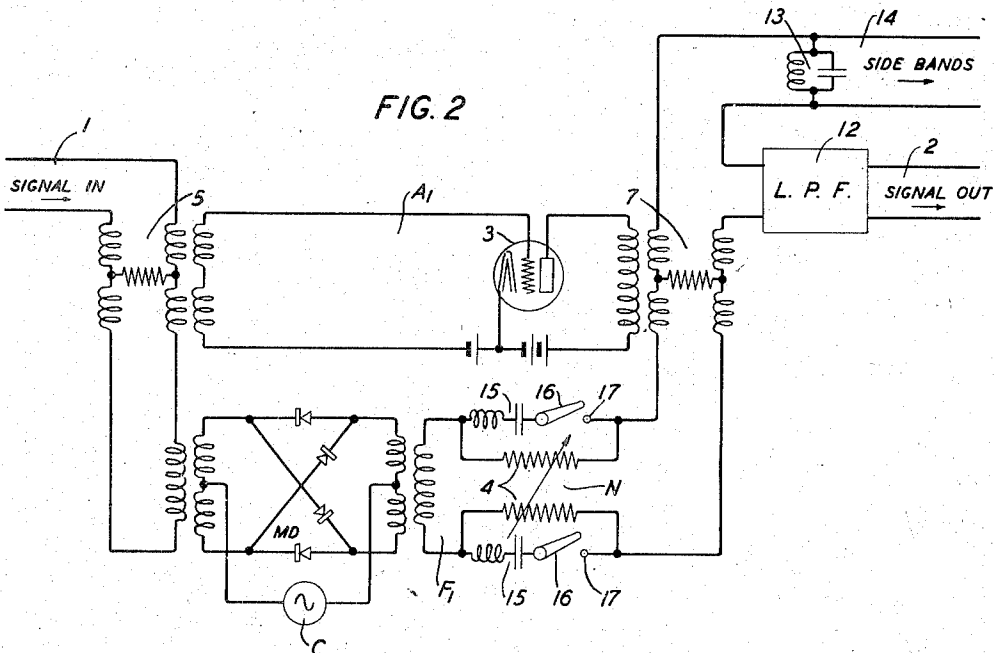


FIG. 2



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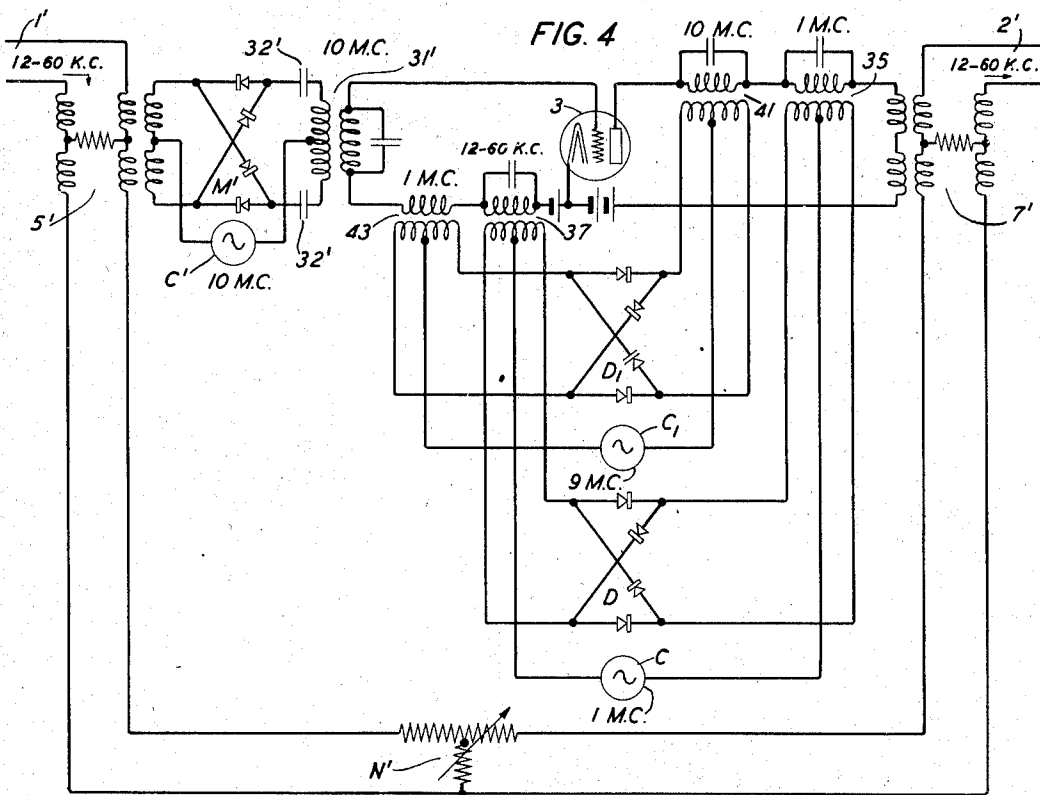
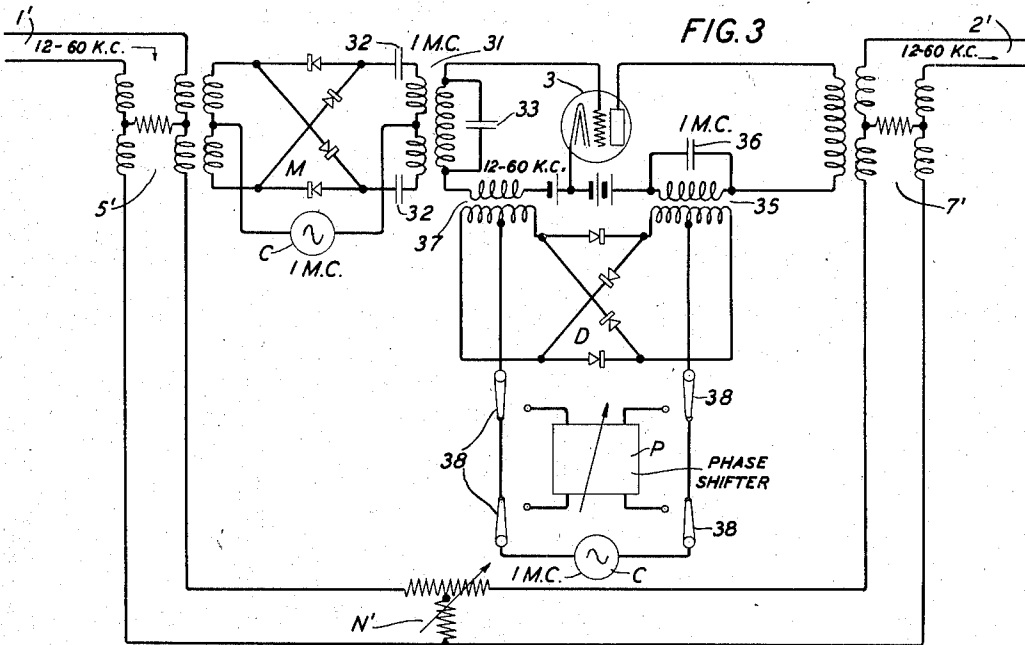
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2 Sheets-Sheet 2



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STABILIZED FEEDBACK SYSTEM

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7 Claims. (Cl. 179-171)

This invention concerns application of negative feedback to wave translating systems, for example, amplifying and modulating systems.

Objects of the invention are to reduce singing tendency in such systems and to increase effectiveness of translating elements of the systems, for example, increase the amplification contributed by given amplifying elements to the systems.

In one specific aspect the invention is a negative feedback amplifier in which signals applied to the feedback loop at a given frequency level pass through a given amplifying device more than once, at a different frequency level each time, in once completing a feedback journey around the feedback loop path with return to the point of application at the given frequency level.

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

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

Fig. 2 shows a modification thereof;

Fig. 3 is a circuit diagram of an amplifier embodying another form of this invention; and

Fig. 4 shows a modification thereof.

In Fig. 1, speech or other signals from line 1 are amplified and the amplified signals are transmitted to line 2. The system comprises an amplifying path A including in addition to a modulating device (modulator-demodulator) MD an amplifying device 3, and comprises a feedback path F including an attenuating network N which may comprise adjustable resistances 4, for example.

Hybrid coil or bridge transformer 5 is an input transformer for the path A, this transformer connecting line 1 to path A with lines 1 and path F in conjugate relation, in the fashion disclosed, for example, in my Patent 2,209,955, August 6, 1940; and hybrid coil 7 is an output transformer for the device 3 and the path A, this transformer similarly connecting path A to line 2, with line 2 and path F in conjugate relation.

The amplifying device 3 may be, for example, a thermionic vacuum tube amplifier comprising one or more cascaded stages of vacuum tubes any of which may be triodes, pentodes or other suitable types of tubes.

Modulator MD may be, for example, a double-balanced copper oxide modulator of the type disclosed in Fig. 2 of F. A. Cowan Patent 2,025,158, December 24, 1935, and in Fig. 2c of

R. S. Caruthers' paper, "Copper oxide modulators in carrier telephone systems," Bell System Technical Journal, April 1939, page 315.

Carrier source C for the modulator may have any suitable carrier frequency C, as for example, one million cycles per second. When supplied with carrier from source C and signal from transformer 5, the modulator suppresses both the carrier and the signal and delivers both the upper and lower side-bands to the input of amplifying device 3. When supplied with carrier from source C and through transformer 5, with side-bands from network N (as described hereinafter), the modulator demodulates the side-bands, suppressing the side-bands and the carrier and delivering the signal to the input of amplifying device 3.

Considering steady state propagation around the feedback loop, the path A and the input and output transformers 5 and 7, as well as the output transformer of modulating device MD, are capable of transmitting the signal frequencies and also both signal side-bands of the carrier frequency C. Signals from line 1 are transmitted through 5 to modulator MD, and there modulated with carrier C to produce the upper and lower signal side-bands of the carrier, which are transmitted from the modulators to the input of 3. These side-bands are amplified (as side-band frequencies) in 3. These amplified side-band components are passed through 7, N and 5 to demodulator MD and there demodulated by carrier C to produce the signals, which are transmitted from the demodulator to the input of 3. These are amplified (as signal frequencies) in 3 and the amplified signals are transmitted through output transformer 7. A portion of their energy goes to line 2, and a portion through network N and transformer 5 to the input of the modulating device MD where this portion thus fed back appears as signals of phase opposite to the phase of the signals transmitted to the input of the modulator MD from line 1 through transformer 5.

If it is desired to suppress transmission of side-band components to line 2, a low-pass filter 12 may be connected between 7 and 2 for transmitting to line 2 the signal frequencies to the exclusion of side-band frequencies.

The μ -circuit of the negative feedback signal amplifier connecting lines 1 and 2 extends from the input of modulator MD through the modulator, device 3, transformer 7, network N, transformer 5, demodulator M, and device 3. Thus the device 3 is included twice in the μ -circuit,

or traversed twice by transmission in passage of the transmission once through the μ -circuit, so the transmission gain that the device 3 inserts in the μ -circuit is twice the decibel gain produced by passage of transmission once through the device 3.

This double inclusion or double gain enables the designer to reduce the number of tubes needed per decibel of $\mu\beta$, and thus the number of tubes needed to obtain by feedback action a specified amount of improvement in transmission, as for example, a specified amount of distortion reduction or of gain stability increase. It is noteworthy that this improvement in transmission applies to the transmission through the modulating device MD, both in modulation and in demodulation, since it is in the passage of the transmission through the μ -circuit that the modulation and the demodulation are effected in the device MD.

Moreover, one of the two passages that transmission makes through device 3 in once traversing the μ -circuit, and also an incidental passage through 1, N and 5, is made at high frequency, the side-band frequencies. This reduces unwanted components of the phase angle of $\mu\beta$ at the frequencies of feedback (i. e., at the signal frequencies), since the high frequency phase shift has little effect on the phase shift between the signal applied from line 1 to the modulator input and the resulting feedback signal (of the same frequency) reaching the modulator input. This reduction in unwanted components of $\mu\beta$ phase shift facilitates design of the feedback system. For example, if no phase shift were introduced by the passage at high frequency, the net effect would be equivalent to amplification without phase shift or amount to increasing the stage gain; and the use of tubes of high stage gain or figure of merit makes it easier to keep a negative feedback amplifier from singing and thus leads to either fewer phase control elements or increased values of feedback.

To explain this feature further, if the frequency of the signal is low compared to the carrier frequency C, then the two side frequencies C+S and C-S represent only a small percentage increase and decrease respectively in the carrier frequency C, and accordingly, a plot of the total insertion phase shift as a function of frequency offered by device MD plus device 3 plus transformers 1 and 5 and network N will be substantially linear over the frequency interval from C-S to C+S. It is known that if the phase shift to the side frequencies is linear with frequency and the modulated wave composed of upper and lower side-bands is demodulated by the same carrier, then the signal is not shifted in phase in traversing the system of modulator, amplifying device and demodulator. It is convenient to note that the extent to which the signal is shifted in phase and changed in amplitude is measured by the envelope propagation, that is, envelope phase and envelope gain.

When the carrier is suppressed as in Fig. 1, then the envelope phase is independent of the signal frequency provided the insertion phase characteristic of the system (from the modulator input to the demodulator output) to the side-band frequencies is either linear or symmetrical about the carrier with respect to frequency and provided further that the gain or loss to each of the side frequencies is equal. However, the transmission or net amplification in stepping the frequency up and down will be dependent upon

the insertion phase of the system to the carrier frequency C. While this dependence can be avoided by using a carrier-transmission system with the demodulator separate from the modulator, it will not be found inconvenient in practice to suppress the carrier provided the phase shift to the carrier frequency C is appreciably different from 90 degrees; because the system from the modulator input to the demodulator output is in the μ -circuit and moderate variations in μ do not appreciably affect the net amplification with feed-back. With a carrier-suppression system the dependence can likewise be avoided by adding phase shift of proper amount, for example, by an adjustable phase-shifting network as indicated at P in Fig. 3 described hereinafter.

Thus, in effect, the over-all $\mu\beta$ which can be plotted as a criterion for stability against singing is made up of two parts, the propagation around the closed loop at signal frequencies multiplied by the envelope propagation around the same parts where the envelope frequency is the signal frequency. Since the phase shift in the latter can be less than the former, the singing tendency is reduced as compared to a single loop of twice as many amplifying parts and no frequency translations.

If desired circuits 15 tuned to the carrier frequency C can be connected in shunt relation to resistances 4 by closing switches 16 on contacts 17, in order to reduce the attenuation of this network at the high carrier or side-band frequencies. Since the transmission of this network at side-band frequencies is in the μ -circuit, this has the advantage of increasing μ and, if desired, $\mu\beta$ of the feedback system. The insertion loss of network N at the signal frequencies, however, controls and varies β and, hence, the over-all gain of the system with feedback.

In certain applications of negative feedback amplifiers it has been found advantageous to vary μ as β is varied, for example, to keep $\mu\beta$ constant. Inasmuch as the attenuation of N in Fig. 1 to side-band frequencies is in the μ -circuit and the attenuation of N to signal frequencies is in the β -circuit, adjusting variable resistances 18, which can be connected in series with circuits 15 by closing switches 16 on contacts 19, values μ and, especially if chokes 20 for the side-band frequencies be added as shown, does not change β . This provides a convenient way of changing μ and β independently, or the resistances 4 and 18 can be appropriately proportioned and ganged together so as to keep $\mu\beta$ constant. For instance, if variable resistances 4 are increased so as to increase the insertion loss of N to the signal frequencies one decibel, the resistances 18 in series with switches 16 can be reduced so as to decrease the insertion loss of network N to side-band frequencies by one decibel.

To illustrate further, if the loss of N to signal frequencies is varied one decibel, the gain of over-all feedback amplifier does not change exactly one decibel because of the so-called " $\mu\beta$ -effect," viz.:

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

where A_F designates the amplification with feedback. If $\mu\beta$ is not sufficiently large compared to unity, this effect may become objectionable in certain refined designs such as a regulating or variable gain broad band repeater and is partic-

ularly objectionable because it varies both with frequency and feedback. However, by holding $\mu\beta$ fixed with respect to the amount of feedback by the expedient of varying each simultaneously by equal but inverse amounts as previously mentioned, the " $\mu\beta$ -effect" is zero.

Fig. 2 is similar to Fig. 1 in configuration, except that MD instead of being in amplifying path A₁ that corresponds to path A of Fig. 1, is in feedback path F₁ that corresponds to path F in Fig. 1, and a frequency selective circuit 13 is shown inserted in series with the input of filter 12, for selecting from the output of transformer 7 for transmission to line 14 sideband components to the exclusion of signal frequency components. For transmission from line 1 to line 14 the system serves as a modulator; and for transmission from line 1 to line 12 the system serves as an amplifier.

In transmission from line 1 to line 2, the signals pass but once through the forwardly transmitting path or μ -circuit A and are amplified by the amplifying device 3 therein; but the passage of the transmission through the β -circuit or retroactive path includes (cascade) passage through F (including MD) from right to left, through 3, and again from right to left through F (including MD). Thus, the amplification of the amplifying device 3 appears in μ but once, or to the first power, and appears to the first power in β and squared in $\mu\beta$. Thus, the system, though actually employing but one amplifying device such as 3, employs such device in the β -circuit as well as in the μ -circuit, thus not only doubling $\mu\beta$ (expressed in decibels), but reducing the difficulty of the problem of preventing singing, and, moreover, increasing the range of gain control by feedback and making lower gain values possible. The system provides amplification in the β -circuit without having to provide extra tubes or amplifying devices for the purpose. This makes it possible to introduce β -circuit networks controlling signal frequencies in location 4 having high values of loss, and, because the β -circuit also has amplification, not increase the gain with feedback to a value that is higher than wanted. In other words, the design of β -circuit networks for equalizing or controlling transmission is facilitated, by increasing their permissible loss.

In operation of the system as a modulator, that is, in transmission from line 1 to line 14, there is negative feedback of signal frequency by a $\mu\beta$ -transmission through a physical loop path which the transmission traverses twice in a single $\mu\beta$ -journey, the transmission experiencing a frequency rise and a frequency fall during its $\mu\beta$ -journey. The μ -journey is from 5 through 3, 7, N, MD, 5, and 3, to 7, the transformer 7 delivering to line 14 the transmission at the side-band frequencies to which the transmission has been raised by modulator MD. In this μ -journey the transmission has passed through 3 twice, once at signal frequencies and once at side-band frequencies, and has passed through MD once. Thus 3 is included in the μ -circuit twice, in effect in tandem connection; and MD is included in the μ -circuit once.

The β -journey is from 7 through N and MD, to 5. Thus 3 is not included in the β -circuit, and MD is included in the β -circuit once, as a β -circuit demodulator.

If desired, the selective circuit 13 and line 14 used in Fig. 2 can be likewise added in the circuit of Fig. 1, so the circuit of Fig. 1 can serve also as a modulator. Then in the operation of the

circuit as a modulator, the device 3 serves as an amplifier in the μ -circuit and also as an amplifier in the β -circuit of the envelope frequency feedback system. Also, if desired the circuit of Fig. 2 may include elements 18 to 20 as shown in Fig. 1.

Fig. 3 shows a circuit for amplifying signals from line 1' and delivering the amplified signals to line 2'. The signals may be, for example, those of a group of twelve speech side-bands of carrier waves in a multiplex carrier telephone system. Modulator M and detector D may be double-balanced modulating devices of the same type as the device MD of Fig. 1. The carrier source C for the modulator M and demodulator D may be the same source and the carrier frequency may be one million cycles per second, for example. The modulator output transformer 31 may be tuned to one megacycle by condensers 32 and capacitance 33. The capacitance 33 may include or may consist of inherent capacitance of the transformer 31 and the inherent input capacitance of amplifying device 3. The demodulator input transformer 35 is connected in the output circuit of the amplifying device 3 and is tuned to one megacycle by capacitance 36, which may be partly or wholly inherent capacitance, as for example inherent capacitance of the transformer and plate-cathode capacitance of the amplifying device 3. The demodulator output transformer 37 is connected in the input circuit of the amplifying device 3 and transmits the signal frequencies to the exclusion of higher frequencies. The bridge transformers 5' and 7', which correspond to bridge transformers 5 and 7 of Fig. 1 transmit the signal frequencies to the exclusion of higher frequencies. A β -circuit network N' connecting 7' and 5' is shown as a network of generalized impedances, and its attenuation plus that of the transformers 7' and 5' in the β -circuit including N' may be substantially equal to the overall gain of the amplifier. In other words, the feedback through N' may be negative feedback sufficiently great to render the over-all gain of the amplifier substantially equal to the loss in the β -circuit in which N' is included.

Signals from line 1' are transmitted through 5' to modulator M, in which they modulate carrier C. The modulator transmits to the amplifier input the two signal side-bands of the carrier C, the secondary winding of transformer 31, (with its inherent shunt capacitance) having negligibly low impedance for these side-band frequencies. The device 3 amplifies these side-band components and transmits the amplified side-bands through transformer 35 to the demodulator D, transformer 7' having negligibly low impedance for the side-band frequencies. The side-bands are demodulated in demodulator D by the carrier C. The resulting signal frequencies of the range 12 to 60 kilocycles are transmitted through transformer 37 to the input of the amplifying device 3 and amplified therein, transformer 31 having negligibly low impedance for these signal frequencies. Transformer 35 has negligibly low impedance for these amplified signals and they are transmitted through transformer 7' to both line 2' and network N', the network N' feeding the signals through transformer 5' back to the input of modulator M in phase opposition to the signals applied from line 1' through 5' to the input of the modulator.

The $\mu\beta$ -path for this negative feedback includes the amplifying device 3 twice in the μ -circuit, the transmission traversing the device

3 once at side-band frequency and once at signal frequency. The amplifier gain reduction (in decibels) effected by the negative feedback, and so the modulation (distortion) reduction effected by the negative feedback (i. e., the improvement in the transmission through the system as regards unwanted modulation arising in the μ -circuit, including unwanted modulator, amplifier and demodulator distortion), is equal to the gain of the amplifier system without the negative feedback minus the gain with the negative feedback; or in other words, neglecting the losses in the modulator and demodulator in the μ -circuit of the amplifier, and assuming the gain inserted by the device 3 at each of the two frequency levels to be G , the improvement due to the negative feedback is equal to $2G-L$, where L designates the loss in the β -circuit (that is, the loss of network N' plus the hybrid coil losses in the β -circuit). Moreover, the process can be repeated so amplification in device 3 will occur n times, to obtain an improvement equal to $(nG-L)$ decibels. An example of this repetition, with $n=3$, is shown in Fig. 4, about to be described. It is noteworthy that since the modulator M and demodulator D are in the μ -circuit, the negative feedback reduces amplifier gain variations due to variation of the amplitudes of the carrier voltages applied to modulator M and demodulator D , as well as gain variations introduced by device 3. More generally, the gain stabilization and other improvements in transmission through the amplifier that are due to the negative feedback, are effective not only with respect to unwanted effects of the device 3 but likewise with respect to unwanted effects of modulator M and demodulator D and any other elements of the μ -circuit.

As indicated above, if desired, the switches 38 can insert adjustable phase-shifting network P between carrier source C and demodulator D , to control the effective insertion phase, at carrier frequency, of the portion of the system from modulator input to demodulator output. For example, the network P may be adjusted to make the non-feedback gain in stepping transmission up and down in frequency a maximum, or in other words, to make the value of $|\mu|$ for the amplifier a maximum.

In Fig. 4, modulator M' corresponds to modulator M of Fig. 3, but is supplied with a ten-megacycle carrier C' from carrier source C' and has its output transformer 31' tuned to ten megacycles by capacitances 32' and 33'. Demodulator D_1 corresponds to demodulator D of Fig. 3, but is supplied with a nine-megacycle carrier C_1 from carrier source C_1 . Demodulator D_1 is added to interpose one additional amplification by device 3 between the amplification at the frequency of the side-bands delivered by modulator M' and the amplification at the signal frequency. The demodulator D may be of the same type as the demodulator D of Fig. 3, and is supplied with a one-megacycle carrier C by carrier source C .

In operation of Fig. 4, signals from 1' are stepped up by modulator M' to the upper side-band and lower side-band of the ten-megacycle carrier. These side-bands are amplified in 3, selected by frequency selective circuit 41, and demodulated by the nine-megacycle carrier in demodulator D_1 . The lower side-band from demodulator D_1 is selected by frequency selective circuit 43 tuned to one megacycle, and is amplified by device 3. This amplified side-band is selected by frequency selective circuit 35 and de-

modulated in D to produce signals, which are selected by frequency selective circuit 37 and amplified (at signal frequency) by device 3. The amplified signals are transmitted through 7' to both 2' and N' , the network N' feeding the signals through transformer 5' back to the input of modulator M' in phase opposition to the signals applied from line 1' through 5' to the input of the modulator.

10 What is claimed is:

1. The method of producing negative feedback of transmission around a closed loop path including a transducer having a pair of input terminals and a pair of output terminals which comprises applying the transmission to a portion of the path, passing the transmission through the path and returning it to said portion in phase opposition to the applied transmission, changing the frequency level of the transmission in its passage through the path and passing the transmission through the transducer from said input terminals to said output terminals a plurality of times at a different frequency level each time in once completing its passage from said portion through the path with return to said portion in phase opposition to the applied transmission.

2. A negative amplifier comprising a closed loop feedback path, means for applying transmission to be amplified to a point of said path at a given frequency level, frequency translating and amplifying means in said path for modulating and amplifying and demodulating and reamplifying the transmission, means in said path for producing negative feedback of the modulated and amplified, demodulated and reamplified transmission to said point of said path at said given frequency level, said second-mentioned means having a given amplifying element with a pair of input terminals and a pair of output terminals, and means in said path for passing the transmission through said amplifying element from said input terminals to said output terminals twice, each time at a different frequency level, in a single feedback journey of the transmission from said point around said path with return to said point at said given frequency level.

3. A wave translating system comprising a wave path, means for applying waves of given frequency level to the input of said path, a modulating device in said path for changing said waves to waves of a different frequency level with suppression of said waves of given frequency level and changing said waves of said different frequency level to waves of said given frequency level, an amplifying device in said path connected in tandem with said modulating device for amplifying said waves of said different frequency level and waves of said given frequency level, and means for feeding said waves of said different frequency level from the output to the input of said path and feeding waves of said given frequency level from the output to the input of said path in phase opposition to said waves applied by said first means to the input of said path.

4. A wave translating system comprising an amplifying device for amplifying waves once at a given frequency level and again at a different frequency level, means for applying waves to the input of said amplifying device at said given frequency level, and a path for transmitting said waves from the output of said amplifying device to the input of said amplifying device with frequency translations each from one frequency

level at the output to a changed frequency level at the input, said path including a modulating device for changing the frequency level of said waves from said given frequency level at the amplifier output to said different frequency level at the amplifier input with suppression of said waves of given frequency level and changing said waves from said different frequency level at the amplifier output back to said given frequency level at the amplifier input and feeding them to the input of said amplifying device in phase opposition to the waves applied by said means to the input of said amplifying device.

5. An amplifier comprising an amplifying path and a feedback path for feeding waves back from the output of said amplifying path to the input thereof in gain-reducing phase, a modulator and an amplifying device in tandem relation in said amplifying path, and a path connecting the output and input of said amplifying device and including a demodulator for demodulating waves from the output of said amplifying device and supplying waves obtained by the demodulation to the input of said amplifying device.

6. A wave translating system comprising a wave path, a circuit for applying waves to the input of said path at a given frequency level, a modulating device in said path for changing the frequency level of said waves from said given frequency level to a different frequency level with suppression of said waves of given frequency level and changing said waves from said different frequency level back to said given frequency level, an amplifying device in said path in cascade connection with said modulating device for amplifying said waves once at said different frequency level and again at said given frequency level, and means for feeding said waves from the output of said path to the input of said path at said

different frequency level and feeding said waves from the output of said path to the input of said path at said given frequency level in phase opposition to said waves applied by said circuit to the input of said path, said means comprising two paths in parallel relation, one more freely responsive than the other to waves of one of said two frequency levels.

7. A wave translating system comprising a wave path, a circuit for applying waves to the input of said path at a given frequency level, a modulating device in said path for changing the frequency level of said waves from said given frequency level to a different frequency level with suppression of said waves of given frequency level and changing said waves from said different frequency level back to said given frequency level, an amplifying device in said path connected in tandem with said modulating device for amplifying said waves once at said different frequency level and again at said given frequency level, and means for feeding said waves from the output of said path to the input of said path at said different frequency level and feeding said waves from the output of said path to the input of said path at said given frequency level in phase opposition to said waves applied by said circuit to the input of said path, said means comprising two frequency selective networks connected in parallel relation, one of said networks passing waves of said given frequency level more freely than waves of said different frequency level and said other network passing waves of said different frequency level more freely than waves of said given frequency level, and means for varying the attenuation of each of said frequency selective networks for waves of the frequency level to which it is selective.

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