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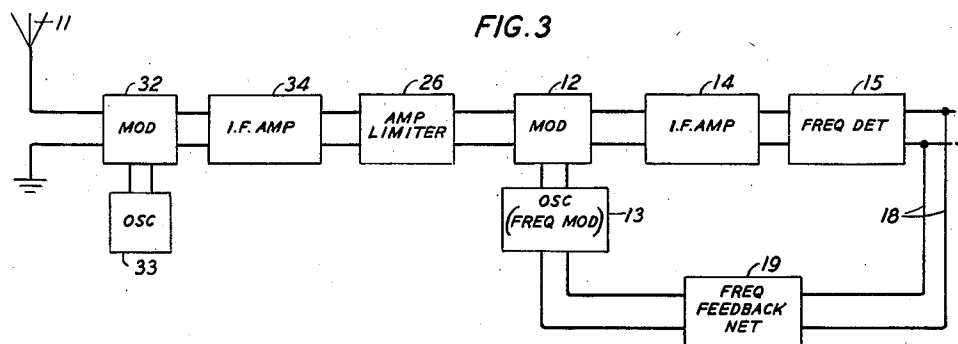
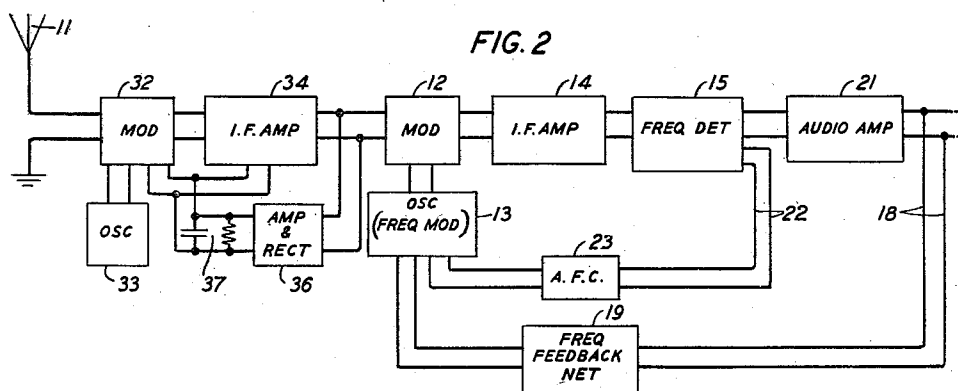
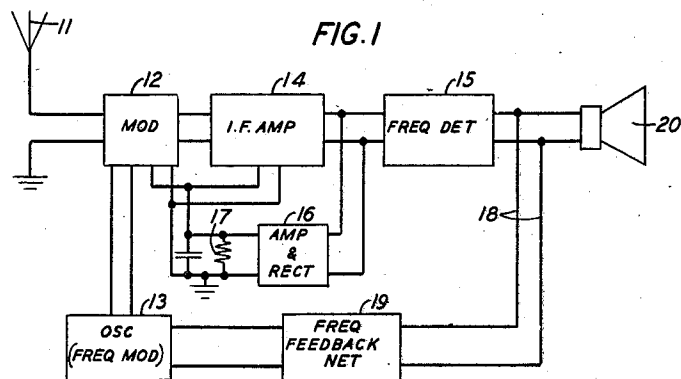
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FREQUENCY MODULATION RECEIVER

Filed Nov. 13, 1940

2 Sheets-Sheet 1



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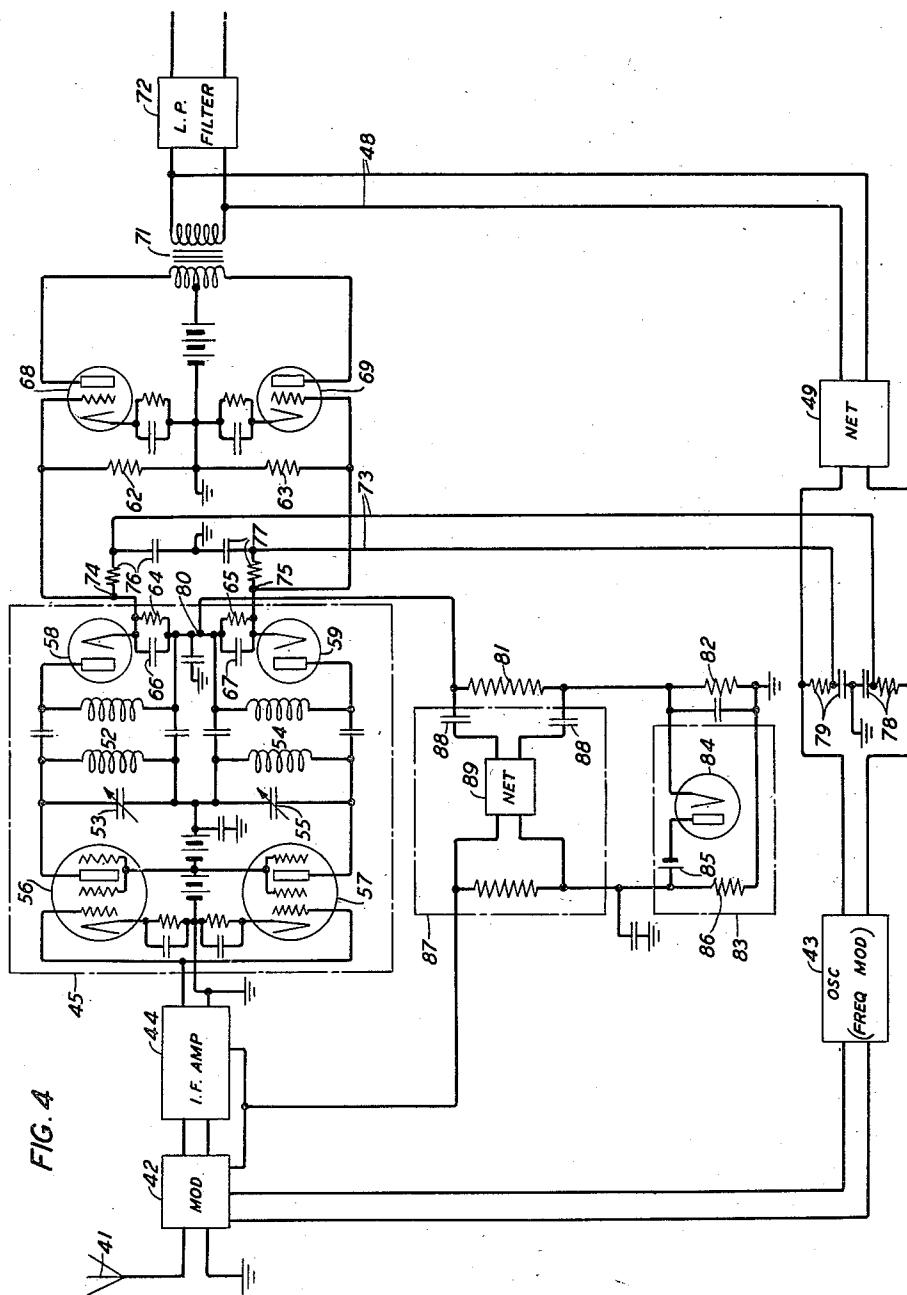


FIG. 4

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FREQUENCY MODULATION RECEIVER

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3 Claims. (Cl. 250—20)

This invention relates to receivers for frequency modulated waves and particularly to receivers of the type covered by my Patent 2,075,503 of March 30, 1937, in which negative feed-back is employed in such a way as to reduce frequency swing.

An object of the invention is to improve the operation of such receivers particularly with respect to their adaptability for operation with incoming signal waves varying in amplitude due to fading or other cause.

In receivers of the type to which the invention relates, negative feedback is applied to a frequency modulation receiver of the superheterodyne type by causing a portion of the detected signal voltage to frequency modulate the beating oscillator in such phase as to reduce the frequency swing of the intermediate frequency wave resulting from the combination of the beating oscillators with the incoming signal. The operation, purpose and advantages of such receiving systems are pointed out in my patent and further discussed in my paper entitled "Application of negative feedback to frequency-modulation systems" published in the Proceedings of the Institute of Radio Engineers, volume 27, pages 317 to 331 (May 1939). Among the advantages of such an application of negative feedback to the receiver is the fact that large reductions of both noise and signal distortion can be achieved. Decided benefits in these directions are realized only when the amount of feedback is substantial by which is meant that the feedback is of such magnitude that the over-all operation of the receiver is substantially independent of the characteristics of the forward acting path. This is analogous to the stabilized condition of an ordinary amplifier employing negative feedback. Also, analogous to the action of such feedback amplifiers, a frequency modulation receiver employing feedback of this type may have a tendency to sing if the feedback characteristics are not properly controlled.

With the ordinary amplifier, the feedback factor is determined only by the circuit characteristics and is independent, within limits, of the amplitude of the input. Consequently, the stability against singing is not affected by variations in the amplitude of the input. I have found, however, that in the frequency modulation receiver, the feedback factor is dependent upon the amplitude of the incoming wave (as will be demonstrated hereinafter) and is dependent in such a way that a system designed to have sufficient stabilized feedback at low field strengths may reach a singing condition at higher field strengths of the received wave.

In accordance with a feature of the present invention negative feedback is employed, as described in Patent 2,075,503, in a receiver for fre-

quency modulated waves and in addition thereto there is employed an independent means for maintaining the amplitude of the high frequency wave within the receiver substantially constant and independent of the received field. In this way the equivalent feedback factor is made independent of the field strength. Among other advantages, this permits the feedback to be made large without danger of the system oscillating at unusually high field strengths, thus permitting the utilization of the full advantages of negative feedback over a wide range of receiving conditions.

In a preferred form of the invention the control of the amplitude of the signals is achieved by regulating the amplification of the signaling wave in the manner of the well-known automatic volume control, i. e., the wave is rectified and the resulting direct current voltage is applied to the grid of the amplifier to regulate its gain. This control of amplitude is preferably accomplished in an amplifier which precedes the modulator stage in which the frequency modulated local oscillations are combined with the received waves, in other words ahead of the feedback loop. This avoids any complication of the circuit of the feedback loop and consequently simplifies the design thereof. However, the control may be applied within the feedback loop, and in some cases this latter arrangement may be found to give certain advantages.

These and other objects, aspects and features of the invention may be more readily understood from the following detailed description in connection with the drawings, in which:

Figs. 1, 2 and 3 are block schematic diagrams of three modifications of the invention; and

Fig. 4 is a detailed schematic diagram of a fourth embodiment of the invention.

In the circuit of Fig. 1 the frequency modulated radio signals received in the antenna 11 are supplied to the modulator 12 which corresponds to the first detector of a superheterodyne receiver. In the modulator 12 the radio frequency signals are combined with oscillations from a beating oscillator 13. This oscillator is of the type in which the generated wave can be frequency modulated by other oscillations, for example, of the Barkhausen type as shown in my Patent 2,075,503 or preferably of the type disclosed in the copending application of O. E. DeLange Serial No. 265,098, filed March 31, 1939, U. S. Patent 2,218,526, dated October 22, 1940.

The intermediate frequency oscillations produced in the modulator 12 by the combination of the received radio waves and the oscillations from the oscillator 13 are amplified in the intermediate frequency amplifier 14. The output of the intermediate frequency amplifier 14 is supplied to two parallel paths. One of these paths

leads to a frequency detector 15. This comprises the usual circuits for detecting the frequency modulated intermediate frequency waves to obtain the modulating audio signals. In the more usual form the detector 15 comprises circuit means for converting the frequency modulation to amplitude modulation, and the usual amplitude modulation detector for reproducing the audio signals therefrom. The output of detector 15 is fed to the signal reproducer 20.

The detected signals appearing at the output of detector 15 are also fed back over the path 18 to the oscillator 13 to modulate the frequency of the currents generated therein. This feedback path 18 includes a feedback network 19 having such transmission characteristics that there may be used an optimum amount of feedback consistent with stability against singing. For detailed information on the control of the circuit characteristics and the design of impedance networks that are suitable for effecting the desired control, reference is made to United States Patent 2,123,178 to H. W. Bode dated July 12, 1938.

As so far described, the circuit of Fig. 1 is similar to the circuits described in my United States Patents 2,075,503 of March 30, 1937, and 2,148,532 of February 28, 1939. The action of the feedback circuit in reducing frequency modulation and diminishing the effects of distortion and noise producing disturbances is particularly explained in Patent 2,075,503.

The receiver of Fig. 1 includes in addition to the circuit elements so far described an automatic volume control amplifier-rectifier 16. The output intermediate frequency from the amplifier 14 is fed to the input of the amplifier-detector 16. The resultant rectified direct current voltage developed across the resistance-capacity network 17 is applied to the control grids of the tubes of the modulator 12 and the intermediate frequency amplifier 14. In this way the gain of these stages is regulated in accordance with the level of the received radio wave to maintain the output of the amplifier 14 of substantially more constant amplitude than the incoming radio waves, as is well known in connection with the operation of automatic volume control circuits.

It is believed that a comprehensive understanding of the cooperative action of the frequency modulation negative feedback and the automatic volume control may best be attained by first considering the operation of the negative feedback circuit alone as set forth in my Patent 2,075,503 and my article in the Proceedings of the Institute of Radio Engineers, referred to above.

Thus, as particularly set forth in the above article, the action of such a system can be described mathematically by an expression which is analogous to that commonly used to delineate the performance of the conventional feedback amplifier. In the case of the feedback amplifier, if μ represents the transmission through the amplifier proper, and β the transmission through the feedback path, a voltage E , applied to the input to the amplifier without feedback will result in an output

$$E_o = \mu E_i \quad (1)$$

When feedback is applied the output becomes

$$E'_o = \frac{\mu E_i}{1 - \mu\beta} \quad (2)$$

so that the gain of the amplifier is reduced by the feedback factor $1 - \mu\beta$. The quantity $\mu\beta$, which is a measure of the amount of the feedback, rep-

resents the transmission gain experienced by the wave in the course of a single traverse of the feedback loop.

As demonstrated in the above-mentioned article, equivalent expressions can be derived to denote the output of the radio receiver in terms of the signal voltage applied at the transmitter and the various circuit parameters which are involved. Thus if E_1 is now used to represent the signal voltage to be transmitted, the signal voltage which is finally detected at the receiver will be, in the absence of feedback,

$$E_o = \alpha a_1 AB \rho_1 E_1 \quad (3)$$

When feedback is applied this becomes

$$E'_o = \frac{\alpha A_1 AB \rho_1 E_1}{1 + \alpha k a_1 AB \rho_2} \quad (4)$$

In these expressions:

α = a constant

a_1 = slope of the gain-frequency characteristic of the receiver

A = voltage impressed upon the modulator by the received wave

B = local oscillator voltage impressed upon the modulator

ρ_1 = modulation sensitivity of the transmitter

ρ_2 = modulation sensitivity of the local oscillator

k = fraction of the receiver output fed back to the local oscillator.

These expressions become identical with those given for the usual feedback amplifier if we write,

$$\alpha a_1 AB = \mu \quad (5)$$

$$k \rho_2 = -\beta \quad (6)$$

It is to be noted that the quantity in Equation 4 corresponding to $\mu\beta$ or the feedback loop gain is dependent upon the strength of the received wave in such a way that it increases in direct proportion thereto.

When the amount of feedback is large the term $\alpha k a_1 AB \rho_2$ is much greater than unity so that the output voltage becomes very closely

$$E'_o = \frac{\rho_1 E_1}{k \rho_2} \quad (7)$$

Thus, the output signal becomes substantially independent of the strength of the received field as well as other factors such as variations in the local oscillator voltage and detector efficiency. This constancy of the signal output may, however, be accompanied by substantial variations of the feedback loop gain, or $\mu\beta$, depending upon the extent of the variation of the received wave strength. The use of such large amounts of feedback also results in very material reductions in noise disturbances and signal distortion originating in the receiver circuit.

With particular regard to the independence of the output signal from variations in the received field, the action may be considered from a somewhat different point of view. Thus, any increase in field strength brings about a corresponding increase in the equivalent μ of the system. This in turn causes the amount of feedback to be correspondingly greater, thus compensating for the higher field. As a result the output signal is restored to its former level.

While this regulatory mechanism is of great value, it can lead to an undesirable condition if the increase in the received field becomes sufficiently great. The reason for this is as follows: In any practical feedback system there exists a definite limit to the amount of stable negative

feedback which can be realized by progressively increasing the product $\mu\beta$. Beyond that limit instability or singing is encountered. The theoretical aspects of this situation are set forth in an article by W. H. Bode entitled "Relation between attenuation and phase in feedback amplifier design" appearing in the Bell System Technical Journal, volume XIX, pages 421-454 (July 1940). Since the negative feedback frequency modulation system is analogous to the negative feedback amplifier, and since the equivalent μ of the system depends directly upon the strength of the received field, it follows that if the field becomes sufficiently intense the amount of feedback which can be applied with stability will be exceeded, and singing will result.

On the other hand, during the periods of very low field strength encountered during deep fading the amount of feedback will be greatly diminished. This is likewise an undesirable condition since the reduction of noise and distortion necessary for the most faithful reproduction of transmitted signal is realized when the amount of feedback is large.

The problem may be summarized by stating that on the one hand a receiver designed for stability against singing for maximum field strengths normally encountered may develop oscillations when the field strength becomes abnormally high. On the other hand, a design that provides stability against singing even for abnormal field strengths may not provide sufficient feedback for faithful signal reproduction during periods of deep fading.

In accordance with applicant's invention these difficulties are overcome in the receiving system illustrated in Fig. 1 by the use of the automatic volume control system 16-17. As previously explained the operation of the automatic volume control amplifier-rectifier 16 in regulating the gain of the modulator 12 and intermediate frequency amplifier 14 is such that the amplitude of the output of the intermediate frequency amplifier 14 is substantially constant and independent of the amplitude of the input to the circuit.

The manner in which this action effects a stabilization of the amount of feedback and tends to hold it at a value determined solely by circuit parameters of the receiver itself can best be shown by an examination of the equations given above, and the manner in which they are modified by the addition of the automatic volume control feature.

Referring to Equation 5, which expresses the equivalent μ of the feedback system, the term a_1 is equal to the slope of the gain-frequency characteristic of the receiver measured between the input terminals of the modulator and the input to the amplitude modulation detector. The slope of this over-all characteristic is proportional to the slope of the conversion circuit characteristic, though it will have a different numerical value, depending upon the amount of amplification which precedes the latter network. If the gain of that portion of the receiver ahead of the conversion circuit is represented by the symbol G , while the slope of transmission curve for the discriminator alone is designated as a'_1 , then it follows that

$$a_1 = Ga'_1 \quad (8)$$

It is here assumed that G is constant over a band of frequencies embracing the useful portion of the discriminator characteristic.

If an automatic volume control circuit is added to the feedback receiver as indicated in Fig. 1, the over-all gain of the modulator and intermediate frequency amplifier is caused to vary in such fashion that, despite changes which may occur in the strength of the received field, the voltage delivered to the frequency detector tends to remain constant. In other words, the gain is automatically regulated in approximately inverse relationship to the received field. The precise relationship can be expressed by an equation similar in form to that describing the performance of any feedback system. In the present instance the relationship between effective receiver gain G and the voltage A impressed upon the input terminals of the receiver is of the form

$$G = \frac{G_0}{1 + mA} \quad (9)$$

where G_0 is the maximum gain which the receiver can assume when the automatic volume control is rendered inoperative, and m is a constant. When a high degree of control is provided, $mA \gg 1$ and

$$G = \frac{G_0}{mA} \quad (10)$$

It then follows from Equation 8 that

$$a_1 = \frac{G_0 a'_1}{mA} \quad (11)$$

Substituting this expression for a_1 in Equation 5 the equivalent μ of the feedback system becomes

$$\frac{\alpha G_0 a'_1 B}{m} \quad (12)$$

which is independent of the received voltage A . Thus the product $\mu\beta$, and hence the amount of feedback becomes independent of any factors external to the receiver.

As has been pointed out above, under any conditions where the feedback factor is considerably greater than unity the output voltage is,

$$E_o = \frac{\rho_1 E_1}{k \rho_2}$$

Consequently, the output signal is independent of fading variations of the incoming wave and accordingly any lack of complete regulation by the automatic volume control as respects the output signal will tend to be removed by the action of the feedback system. More properly speaking the automatic volume control serves to maintain the amount of feedback constant and in conjunction with the action of a strong feedback, thus made feasible, results in an extremely constant output level.

Fig. 2 shows a radio receiver embodying a modified form of the invention. In this figure the circuit elements which are analogous to and perform the same functions as corresponding elements of Fig. 1 have been given the same reference numerals.

The circuit of Fig. 2 differs from that of Fig. 1 essentially only in that the automatic volume control is applied to stages ahead of the modulator of the feedback system. This simplifies the feedback problem particularly with respect to the design for providing stability against singing. This may be advantageous for certain purposes though on the other hand for other purposes, particularly for operation under conditions of high noise levels, it may be desirable to include as many of the amplification stages as possible in the feedback loop.

The radio receiver of Fig. 2 is of the triple de-

tection type. The radio signals received by the antenna 11 are supplied to the modulator 32 where they are combined with the oscillations from an oscillator 33 of conventional design, and preferably crystal controlled. The resulting first intermediate frequency output of the modulator 32 is selectively amplified in the first intermediate frequency amplifier 34.

The gain of the modulator 32 and intermediate frequency amplifier 34 is regulated by means of the automatic volume control circuit comprising the amplifier-rectifier 36 and the resistance-capacity network 37.

The remainder of the receiver of Fig. 2 comprises a negative feedback system as is shown in Fig. 1 and my previous patents. This includes the modulator 12, frequency modulated oscillator 13, intermediate frequency amplifier 14, frequency detector 15, audio amplifier 21, and feedback path 18 including the frequency feedback network 19.

In addition there is shown a connection 22 from the frequency detector 15 and including the automatic frequency control path 23. This is in accordance with the circuit of Fig. 2 of my Patent 2,075,503 and is for the purpose of maintaining the mean frequency of the oscillator 13 at such value that the mean frequency of the intermediate frequency output of the modulator 12 is constant. It is, of course, understood that this feature may be, and in any practical installation usually will be, employed in the type of system of Fig. 1, but has been omitted therefrom for the purpose of simplifying the explanation.

In the operation and theory of the circuit of Fig. 2 the equivalent μ of the feedback system and consequently the feedback factor will be a function of the amplitude of the input to the modulator 12. However, the operation of the automatic volume control circuit 36-37 will tend to maintain this amplitude constant so that in effect the operation of the feedback system will be the same as that of Fig. 1.

Fig. 3 shows a modification of the system of Fig. 2. In the circuit of this receiver the amplitude limiter 26 is utilized in place of the automatic volume control system. The effect of the amplitude limiter 26 will be equivalent to that of the automatic volume control circuit, namely to maintain the amplitude of the input to the modulator 12 constant.

Fig. 4 shows another modification of the invention in a radio receiver. In this circuit the frequency modulated radio waves received in the antenna 41 are supplied to the modulator 42 wherein they are combined with the output of the oscillator 43 which is frequency modulated by the detected signals supplied through the feedback path 48.

The oscillator 43 is preferably of the type disclosed in the patent of O. E. De Lange referred to above. The output of the modulator 42 is supplied to the input of the intermediate frequency amplifier 44 wherein the intermediate frequency waves from the modulator 42 are selectively amplified.

The frequency detector 45 is connected to the output of amplifier 44. This detector consists of two amplifier tubes 56 and 57 provided with selective output circuits by means of which the frequency modulations are converted into amplitude modulations. The desired conversion characteristic is provided by interstage networks 52, 53 and 54, 55. Inductances 52 and 54 are each formed by winding two closely adjacent

strands of insulated wire on a common coil form so as to provide extremely close coupling between the two helices. These are effectively in parallel at high frequencies, but provide insulation between the plate potential supply for tubes 56 and 57 and the diodes 58, 59. Composite coils 52 and 54 are tuned by means of condensers 53 and 55, respectively, one circuit being tuned to a frequency above that of the unmodulated intermediate frequency wave and the other to a frequency a corresponding amount below. At a frequency corresponding to that of the intermediate carrier the transmission through the two branches of this balanced conversion system should be equal so that like voltages are applied to the anodes of rectifiers 58, 59.

The resultant amplitude modulated waves are applied to the diode detectors 58 and 59 which operate as linear rectifiers. The resultant signal voltages across the detector load resistors 64 and 65 are impressed on the grids of the push-pull connected amplifier tubes 68 and 69. The output of this push-pull amplifier appearing in the secondary of the transformer 71 is supplied through the low pass filter 72 to the utilization circuit.

The secondary of transformer 71 is also connected through the feedback circuit 48 to the oscillator 43 for frequency modulating the oscillator output. This feedback circuit includes the feedback network 49, the purpose of which, as explained in connection with the corresponding network of Fig. 1, is to permit such control of the characteristics of the feedback factor as to produce an optimum amount of feedback consistent with stability against singing.

As long as the mean frequency of the intermediate frequency wave remains at its normal value (the cross-over point of the characteristics of circuits 52, 53 and 54, 55) the average value of the total drop across resistors 64 and 65 will be zero. Any variation of the intermediate frequency from this normal value will produce a variation in the average voltage between points 74 and 75 depending not only in value but also in sign, upon the extent and direction of the variation.

The voltage between points 74 and 75 is applied to the circuit 73 through the resistance-capacity networks 76 and 77. These networks prevent any application to the circuit 73 of voltages of signal frequency, limiting the voltages to the slow variations in the mean value of the intermediate frequency. This frequency control voltage is combined with the signal voltage feedback in the output of network 49 and applied to the oscillator 43 to regulate its frequency so as to correct for such slow drifts of the intermediate frequency. This separation of the feedback and frequency control paths is similar to that of Fig. 2 of my Patent 2,075,503. The networks 78 and 79 provide means for combining the two paths for application to the frequency modulated oscillator 13.

In addition to the voltages developed by the detector tubes 58 and 59, as already discussed, there is also developed between the point 80 and ground rectified carrier voltage, noise voltages resulting from amplitude modulation of the incoming carrier by high frequency disturbances and even-order products generated in the detection process. These voltages are developed across the resistors 81 and 82 which are connected between the point 80 and ground. These two resistors provide means for utilizing both the

direct and alternating current components and separately treating them.

The direct current component developed across resistor 82 is utilized for automatic volume control in a similar way to the direct current developed across the resistor 17 of Fig. 1. The network 83 provides means for the so-called delayed automatic volume control action so that control does not come into action until the received radio signal reaches a predetermined level and the full amplification of the tubes is available for low signal levels below that point. For this purpose a diode tube 84 is connected in series in the automatic volume control lead. A battery 85 biases the anode of this diode 84 negative with respect to its cathode. In this way the path for the control voltage is made non-conductive and no automatic volume control action takes place until the voltage across resistor 82 exceeds the bias voltage 85. In the presence of voltages above this level the direct current voltage developed across resistor 86 is applied to the grids of the tubes of the modulator 42 and intermediate frequency amplifier 44 to regulate their gain.

In addition the alternating current voltages developed across resistor 81 are also fed back to the grids of the tubes of modulator 42 and amplifier 44 through the circuit 87. The blocking condensers 88 provide means for preventing any direct current feedback through this path. The network 89 provides means for controlling the transmission characteristic of this path to provide stability against singing, as is well understood in connection with the application of negative feedback to amplifiers.

As was pointed out above, these alternating current voltages appearing across resistor 81 comprises noise currents, resulting from amplitude modulation and even-order products generated by the detector operation. From a theoretical standpoint none of these products appears between the points 74 and 73 as long as the detector circuit is balanced. However, in practice such a perfect balance cannot be maintained at all times. Consequently the reduction of such products by the negative feedback through the circuit 87 provides a practical advantage.

The negative feedback through the circuit 87 provides another benefit. With the frequency modulation feedback through the circuit 48, oscillator 43 and modulator 42, the ratio of signal level to the level of the noise which exists in the absence of signal modulation in the incoming wave is the same as would result from an elimination of amplitude modulation effects by amplitude limitation or other means. During modulation periods the noise level may increase from this point by a small amount, depending upon the ratio of the actual frequency deviation of the intermediate frequency wave to the highest frequency to which the output circuit is responsive. By the negative feedback of the noise voltages resulting from amplitude modulation this noise increment accompanying modulation is eliminated. This circuit has the advantage over the use of amplitude limiters for producing a similar effect in that the effect is produced without any reduction or loss in carrier amplitude inherent in the use of amplitude limiting.

What is claimed is:

1. A receiver for waves modulated in frequency in accordance with a signal, a source of heterodyne oscillations, a modulator for combining the received waves with oscillations from said source, an amplifier for the intermediate frequency output of said modulator, means for detecting the frequency modulations of the output of said amplifier to reproduce the signal, means for frequency modulating the output of the said source by the signal voltage produced by the detecting means, means for producing a direct current voltage proportional to the amplitude of the output of said amplifier, means responsive to said direct current voltage for regulating the gain of said amplifier to maintain the output amplitude substantially constant, means for producing an alternating voltage proportional to the amplitude modulations of the output of said amplifier, and a negative feedback path for supplying said alternating voltage to the input of said amplifier.

2. A receiver for frequency modulated waves comprising a source of heterodyne oscillations, a modulator for combining the oscillations from said source with the received frequency modulated waves, an intermediate frequency amplifier for selectively amplifying the intermediate frequency output of said modulator, two detector circuits having impedance characteristics substantially equal at the mean frequency of said intermediate frequency, circuit connections for supplying the output of said intermediate frequency amplifier to said detector circuits, a first output circuit for combining the outputs of said detector circuits in phase opposition, a second output circuit for combining the outputs of said detectors in aiding phase, means for supplying the voltage from said first output circuit to said heterodyne source to frequency modulate the output thereof in such a sense that when said output is combined with the received waves in said modulators the frequency swing of the intermediate frequency output is less than that of the received wave input, means for supplying the alternating components of the voltage from said second output circuit to the input of the intermediate frequency amplifier in such a sense as to oppose similar components of the intermediate frequency input to said amplifier, and means for supplying the direct current components of the voltage from said second output circuit to said intermediate frequency amplifier to regulate the gain thereof so as to maintain the output amplitude more constant than the input amplitude.

3. A receiver for waves modulated in frequency by a signal comprising an amplifier for the frequency modulated wave, two detector circuits connected to the output of said amplifier said two detector circuits producing signal currents of opposite phase from the amplified frequency modulated waves, a first output circuit in which the signal current outputs of said two detectors are combined in phase opposition, a second output circuit in which the outputs from said two detectors are combined in like phase, and a feedback circuit from said second output circuit to the input of said amplifier for the alternating components of the voltage in said second output circuit whereby similar components of the input to said amplifier are reduced.

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