Nov. 22, 1949 M. S. CORRINGTON 2,488,585

FREQUENCY MODULATION RECEIVER

Filed May 29, 1945 2 Sheets-Sheet 1

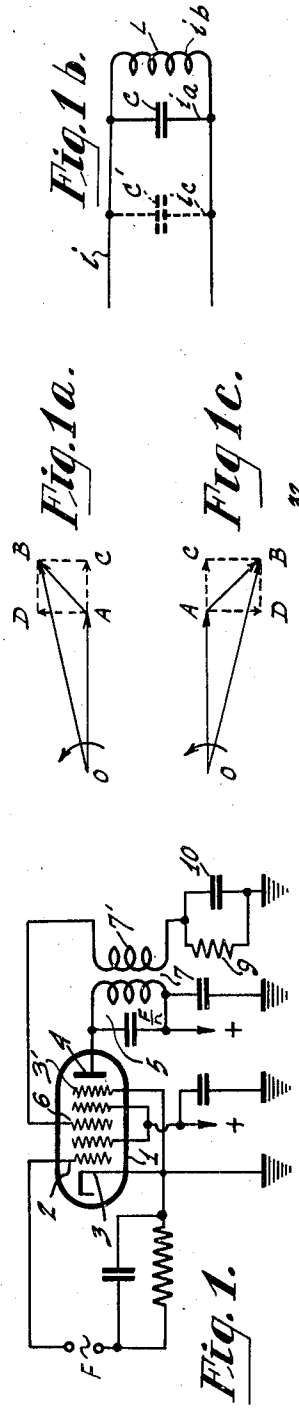


Fig. 1.

Fig. 1a.

Fig. 1b.

Fig. 1c.

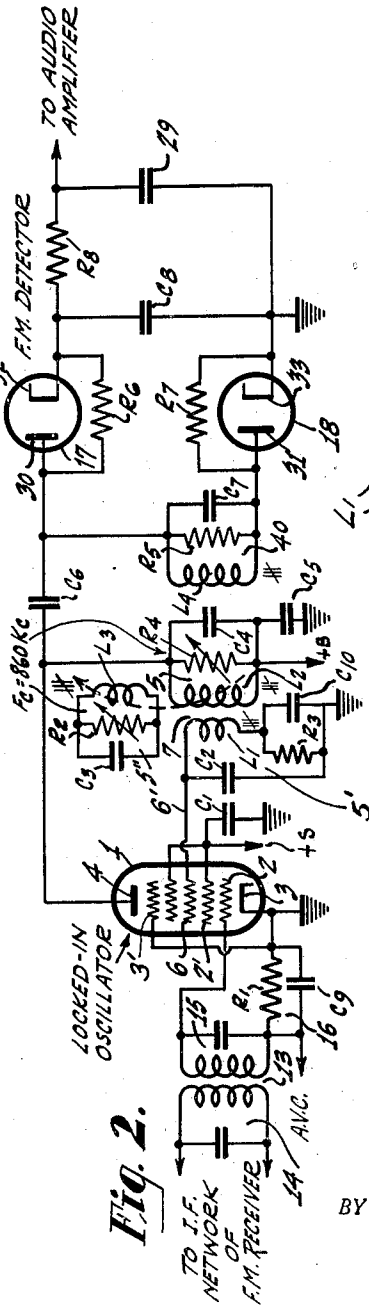


Fig. 2.

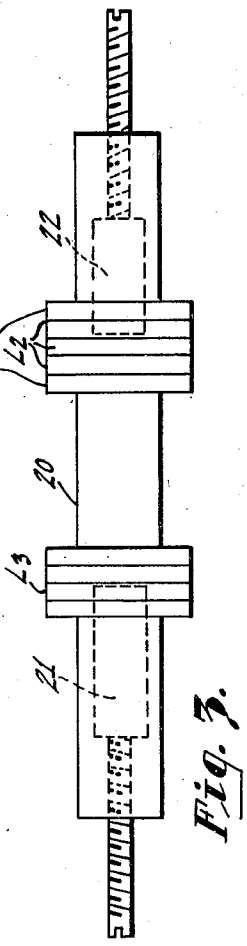


Fig. 3.

INVENTOR.
MURLAN S. CORRINGTON
BY H. S. Grover
ATTORNEY

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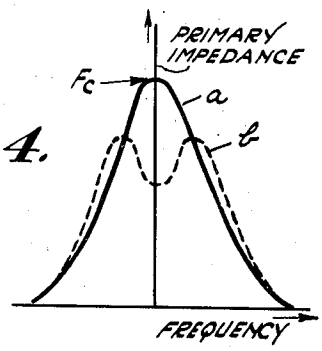


Fig. 4.

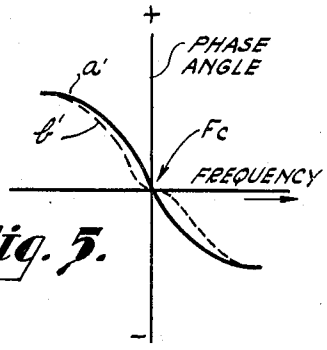


Fig. 5.

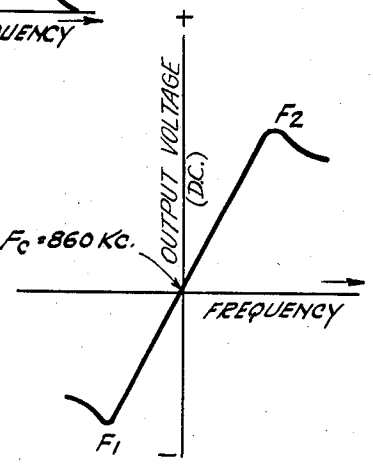


Fig. 6.

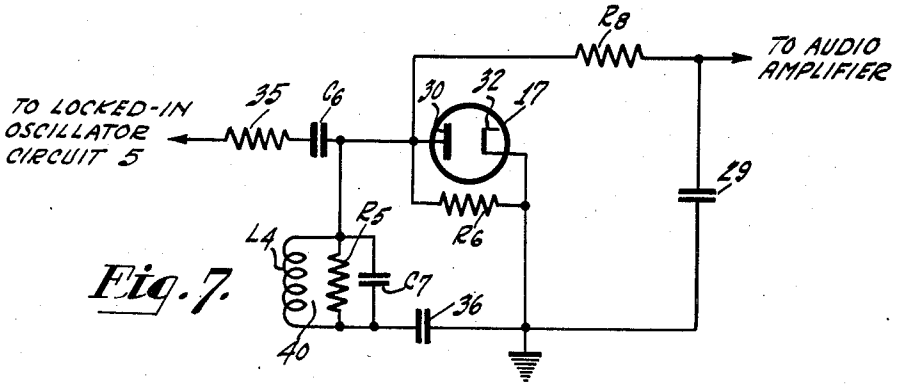


Fig. 7.

INVENTOR.
MURLAN S. CORRINGTON
BY H. S. Grover
ATTORNEY

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UNITED STATES PATENT OFFICE

2,488,585

FREQUENCY MODULATION RECEIVER

Murlan S. Corrington, Camden, N. J., assignor to Radio Corporation of America, a corporation of Delaware

Application May 29, 1945, Serial No. 596,474

6 Claims. (Cl. 250—20)

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My present invention relates generally to frequency modulation receivers utilizing locked-in oscillator circuits, and more particularly to novel means for extending the lock-in range of frequency dividers of the locked-in oscillator type and detecting the output thereof.

In my application Serial No. 513,371 filed December 8, 1943, I have disclosed and claimed novel circuits for receiving angle-modulated carrier waves and employing a locked-in oscillator system acting as a frequency divider. These circuits were improvements on the locked-in oscillator circuit disclosed and claimed by G. L. Beers in his U. S. Patent No. 2,356,201, granted August 22, 1944.

In the operation of the Beers circuit angle modulated waves of a predetermined mean or center frequency F are applied to the input control grid of a tube which may be of the pentagrid type, the output or plate electrode circuit being tuned to a desired subharmonic F/n, where n is a small integer. In the illustrative embodiment described in the Beers patent, the 5th subharmonic is developed across the plate circuit, i. e., $n=5$. For some purposes it is desirable to extend the lock-in range of the circuit shown in Fig. 1 of the Beers patent, while still retaining the advantages of a lock-in range limited to suit the requirements for best reception of the incoming signal. Moreover, I believe the operation of the locked-in oscillator shown in the Beers patent depends upon harmonics, especially the 4th and 6th harmonics in the example given, of the oscillator frequency beating with the incoming frequency and thereby producing an injected frequency which controls the oscillator frequency. As will be further described below, such injected frequency will be higher or lower than the mean oscillator frequency as the incoming frequency varies above or below its mean frequency.

An important object of my present invention is to provide a locked-in oscillator of wide lock-in range whose constants are variable thereby to secure ready control thereof. To this end, my invention facilitates the control of the oscillator frequency by the injected currents produced as the incoming frequency differs from its mean frequency.

My aforesaid application provided one method of increasing the lock-in range of a locked-in oscillator of the type shown in the aforesaid Beers patent. The method comprised tuning the oscillator plate circuit sufficiently to one side of F/n so that it would readily lock-in on one end of the frequency swing, and tuning the oscillator grid

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circuit sufficiently on the other side of the desired harmonic

$$\frac{4F}{n} \text{ or } \frac{6F}{n}$$

to help lock-in the oscillator on the opposite end of the swing.

In my application Serial No. 563,379, filed November 14, 1944, now Patent No. 2,440,653, granted April 27, 1948, I provided a novel method, distinct from that disclosed in my aforesaid application, of increasing the lock-in range of a locked-in oscillator by adding an electrical network in parallel with the oscillator tuned output circuit, and adjusting the added electrical network so that the equivalent input capacity decreased at the proper rate to just keep the oscillator in tune throughout most of the operating range. The equivalent series capacity of the network was chosen to vary with frequency at the proper rate to keep the oscillator in tune for a portion of the lock-in range. One suitable added electrical network was the discriminator input circuit of an FM detector of the type shown by J. D. Reid in U. S. Patent No. 2,341,240, granted February 8, 1944, where the said discriminator was desired to be shunted directly across the plate circuit of the locked-in oscillator. Hence, the design of the FM detector in that case was restricted by the fact that its input was a part of the locked-in oscillator. The FM detector of the said Reid patent is highly desirable from the viewpoint of linearity of detection. At the same time it is equally desirable, especially in the servicing of FM receivers, to have the characteristics of the locked-in oscillator substantially independent of those of the FM discriminator.

It is, therefore, an important object of my present invention to provide such substantial independency, while utilizing a highly linear FM detector and securing a relatively wide lock-in range for the locked-in oscillator.

Another important object of my invention is to provide an improved Reid type FM detector whose load resistors are arranged to provide control over the FM detection characteristic.

Still other objects of my invention are to improve generally the efficiency, reliability and operation range of locked-in oscillators, and more especially to provide locked-in oscillators of extended operation range which are economical in construction and assembly.

Still other features of my invention will best be understood by reference to the following description, taken in connection with the drawings,

in which I have indicated diagrammatically several circuit organizations whereby my invention may be carried into effect.

In the drawings:

Fig. 1 shows the basic locked-in oscillator circuit of the aforesaid Beers patent;

Figs. 1*a*, 1*b* and 1*c* are employed to analyze the circuit action thereof;

Fig. 2 shows schematically an embodiment of my invention;

Fig. 3 shows the construction of the locked-in oscillator transformer;

Fig. 4 graphically shows ideal response curves for the tank circuit of the locked-in oscillator;

Fig. 5 shows the phase angle shifts corresponding to the curves of Fig. 4;

Fig. 6 shows a typical linear FM detection characteristic; and

Fig. 7 illustrates a modified detector.

Referring now to the accompanying drawings, wherein like reference numerals in the different figures designate similar circuit elements, reference is made to the circuit shown in Fig. 1 for an explanation of the fundamental mode of operation of a locked-in oscillator which is of the general type shown in the aforesaid Beers patent. The circuit comprises a tube 1 which may be of the pentagrid type, but may also be of many other types capable of use as an oscillator. Between the input grid 2 and the cathode 3 there is impressed high frequency energy of a predetermined frequency F. The plate 4 has connected in circuit therewith a resonant circuit 5 which is tuned to a subharmonic F/n of F, the symbol n denoting a small integer. By way of illustration, the fifth subharmonic may be employed. However, a 3:1 or 4:1 or other frequency division ratio may be used. The plate 4 is, of course, established at a positive direct current potential with respect to the grounded cathode. The second and fourth grids of the tube are connected in common to a source of positive direct current potential, and these grids function as a positive screen grid for the intermediate grid 6. As shown the coil 7' has its lower end connected to ground through the resistor 9, and the latter is bypassed for high frequency currents by the condenser 10.

The grid 6 is regeneratively coupled, as at 7, to the plate circuit 5. The fifth grid 3' of tube 1 is connected back to the cathode, and this grid, therefore, functions as a suppressor grid. The cathode 3, grid 6 and plate 4 provide the oscillator section of the circuit. This oscillator section produces oscillations of the subharmonic frequency F/n. These oscillations are continuously produced even in the absence of input energy at grid 2. The oscillations developed across circuit 5 may be transferred to any utilization network.

To aid in imparting a more ready understanding of my invention, I shall first state what I believe to be the best explanation of the manner of operation of the locked-in oscillator shown in Fig. 1. The current from the tube is not sinusoidal, but comes through as a series of pulses. These cause harmonics of the subharmonic frequency F/n to be developed in the plate circuit 5. These harmonics will be applied to the grid 6 because of the coupling 7. Furthermore, the grid 6 is operating with self-bias, and draws grid current during the positive swings of voltage. These pulses, also contain harmonics of F/n.

Let us assume by way of illustration that F has a value of 4300 kilocycles (kc.), which may be the intermediate frequency of a superheterodyne FM broadcast receiver. This frequency will beat with the fourth (3440 kc.) and/or sixth (5160 kc.) harmonics of the resonant frequency of the plate circuit thereby to provide the desired subharmonic of 860 kc. In this case it is assumed that n is equal to 5. When the fourth and sixth harmonics are present simultaneously, it can be shown that the result is a single injected current of variable amplitude and phase. The process is similar to that when only one harmonic is present. Usually the fourth and sixth harmonics will be of unequal amplitude, and the effect of the weaker one is to produce relatively small variations in the other. When the frequency of the incoming signal is exactly five times the natural frequency of the oscillator, the harmonic difference component will be in phase with the current in the oscillating plate circuit. The circuit becomes stable in this condition, and the injected current will lock-in the incoming 4300 kc. signal with the 860 kc. current in the plate circuit. Since the injected current has the same phase and frequency as the normal current in the plate circuit it is equivalent to an increased output from the tube.

Now assume for the moment that the incoming frequency is higher than 4300 kc. and is within the lock-in range, but that the oscillator has not yet locked-in. The effect of the fourth harmonic and the incoming frequency will be to inject a current of slightly greater frequency than 860 kc. into the tank circuit. In Fig. 1*a*, OA is a vector assumed to be rotating 860,000 times per second, and represents the normal current in the oscillator tank circuit. Let AB be a vector representing the instantaneous injected current of frequency slightly greater than 860 kc., resulting from the fourth harmonic of the oscillator voltage beating with the incoming signal voltage. This vector will rotate slightly faster than 860,000 times per second, and thus will have an angular velocity relative to OA equal to the difference of the two angular velocities.

Consider, further, the instantaneous condition shown in Fig. 1*a*. The injected current AB has a component AC, shown dotted, in phase with OA and another component AD (shown dotted) 90° out of phase with respect to OA. The vector OB represents the resultant of OA and AB. Let this current OB be applied to a tuned circuit LC as shown in Fig. 1*b*. Since the circuit LC is tuned to 860 kc., it will be at resonance with respect to the current OC, which is also 860 kc., and equals i_a+i_b. The quadrature current AD is a leading current at the instant shown in Fig. 1*a*, and the result is the same as though an additional condenser C' is connected in the circuit LC. The effect is to decrease the natural frequency of the tuned circuit LC.

Now consider the condition at a later instant, as shown by Fig. 1*c*, the incoming frequency being the same as in the preceding discussion of Fig. 1*a*. The oscillator has not yet locked in. The vector AB has rotated to the new position as shown. The injected current AB now has an in-phase component AC as before, but the component AD is now lagging instead of leading. If the current OB is now impressed on the circuit of Fig. 1*b*, the lagging component AD will cancel part of the leading current through capacitor C, and this will be equivalent to reducing the capacity of C since it is now drawing a smaller leading current. This will raise the resonant frequency of the tuned circuit LC.

It is evident that the circuit of Fig. 1 behaves like a reactance tube circuit. It is easy to see that if the frequency of the incoming signal is

approximately five times that of the frequency of the tuned circuit 5, a point will be reached when the frequency of the tuned circuit becomes exactly one-fifth of the incoming signal frequency. When this happens the oscillator will "lock-in" with the incoming signal. This means that the amplitude and phase of the plate current now remain fixed with respect to the incoming signal.

If the incoming signal is exactly five times the frequency of the tuned plate circuit, the vector AB will be in phase with OA. As the incoming signal frequency is decreased the oscillator remaining locked in with it, the vector AB rotates to some position such as that shown in Fig. 1*a*. A further decrease in frequency will rotate the vector until it is 90° out of phase with respect to OA. Since this position gives the maximum amount of quadrature current it corresponds to the maximum amount that the oscillator frequency can be pulled over, and thus gives the lower limit of the lock-in range. If the incoming signal frequency becomes greater than five times the plate circuit frequency, the conditions will be similar except that the vector AB will be lagging, as shown by Fig. 1*c*, instead of leading. The upper limit of the lock-in range is reached when the injected current lags by 90°. The lagging current tends to reduce the effective capacity of the circuit, and thus raises the frequency.

The amount of fourth and/or sixth harmonic current which is applied to grid 6 is limited. This limits the lock-in range of the oscillator, since it limits the amount of the above-mentioned injected current. The result is that when the deviation of the incoming signal from 4300 kc. exceeds approximately ±30 kc., the oscillator suddenly breaks out and the frequency goes back towards center (860 kc. in the example herein described). This means that the oscillator is no longer locked in; the ratio of the incoming frequency to the oscillator frequency is no longer a definite small integer. If the oscillator is being used as a secondary frequency standard, to compare two frequencies, to operate a clock or in an FM receiver, this "break-out" will be objectionable. The figure of ±30 kc. as the approximate "break-out" point is for the conditions shown in Fig. 1, i. e. the oscillator is operating without a frequency discriminator or other auxiliary circuit to extend the lock-in range and the grid circuit is not tuned.

In an FM receiver this will cause distortion. The practical operating disadvantage of this "break-out" effect in an FM receiver resides in the fact that if a receiver is mistuned slightly, the "break-out" will occur on one end of the frequency swing and even for normal frequency swings. Such mistuning of a receiver is quite possible, since the average operator of a frequency modulation receiver finds it difficult to tune the receiver exactly. Again, if the FM transmitter station overmodulates, the "break-out" can occur on both ends of the frequency swing. Also, gradual drifts in frequency of the heterodyne oscillator and other circuits, due to temperature or other changes during operation, may cause mistuning and consequent "break-out."

In accordance with my present invention the "break-out" effect is substantially eliminated by extending the lock-in range of the oscillator. In accordance with my present invention, and contradistinct from the methods of my aforesaid applications, there is provided an auxiliary resonant network which is inductively coupled with the

tuned plate circuit of the oscillator. This added, or auxiliary, resonant network is adjusted in resonance so that it retards the phase shift of the plate current with changing frequency at the proper rate to just keep the oscillator in tune throughout most of the operating range. This makes it possible to lock in the oscillator over a greater frequency range for a given amount of injected current. It should be noted that when a network is designed so that the oscillator is in tune over a given band of frequencies, the reactance of the oscillator circuit is zero over the same range. This means that the phase-angle characteristic (plate voltage with respect to plate current) is also zero in this range. Therefore, the functioning of the auxiliary resonant network coupled to tank circuit 5 can be explained in terms of the addition of a network so designed that the phase characteristic of the combination is zero in the desired range.

In Fig. 2 I have shown a circuit embodying my invention for extension of the lock-in range of the oscillator section of a frequency divider and ensuing discrimination of FM signals. The system shown in Fig. 2 includes the locked-in oscillator acting as a frequency dividing network in a receiving system of the type disclosed in the aforementioned Beers patent. The locked-in oscillator functions concurrently to reduce or divide the mean frequency of the applied FM signal waves, and proportionately to reduce the extent of frequency deviation of the waves. Assuming that the FM receiver is of the superheterodyne type and that the networks prior to the locked-in oscillator tube are conventional in nature, the transformer 13 will have its primary circuit 14 and its secondary circuit 15 each tuned to the operating intermediate frequency (I. F.) of the system.

The received FM waves may be those which are transmitted in the present assigned FM band of 42–50 megacycles (mc.) or may be in the 84–102 mc. range proposed for the future. The invention is not limited to any particular frequency band or to the reception of FM waves, since it is generally applicable to angle modulated carrier waves. Those skilled in the art are fully aware of the fact that in each channel the FM waves transmitted in the aforementioned assigned FM band are presently allotted a maximum overall frequency swing of 150 kc. with respect to the mean or center frequency F_c, Fig. 4. The frequency deviation at any instant is dependent upon the amplitude of the modulation signals at the transmitter, while the time for a cycle of the frequency deviation is equal to the period of the modulating signal per se.

The collected FM waves are usually selected in one or more stages of tunable radio frequency amplification, after which they are combined with locally-produced oscillations at the first detector network. The output of the first detector or converter is the I. F. (intermediate frequency) energy. In other words, the I. F. energy is the FM wave whose mean frequency has been reduced to a much lower frequency, but whose frequency deviation is unchanged. After amplification by one or more stages of I. F. amplifiers, the I. F. energy is applied to the locked-in oscillator for concurrent frequency division and reduction of the frequency deviation. The mean frequency of the I. F. amplifier is located at 4.3 mc., whereas the pass band of the network is more than 150 kc. wide. It is believed that a width of 200 kc. will usually provide suitable tolerances. This

signifies that the network 14, 15 is capable of efficiently transmitting the entire frequency swings of the FM wave whose mean frequency has been reduced to the operating I. F. value. While the value of 4.3 mc. has been assigned as the operating I. F. value, it is to be clearly understood that any other satisfactory value may be employed depending upon the various factors met with in the design of the receiver.

The FM signal energy with its mean frequency at the operating I. F. value is applied to the input grid 2 of tube 1. The latter may be, for example, a miniature tube of the pentagrid type. The input grid 2 is connected to the high alternating potential side of the secondary circuit 15. The low potential side of circuit 15 is returned to the grounded cathode 3 through a resistor R_1 shunted by condenser C_9, the latter comprising a network designated by the numeral 16. The function of the network 16 is to provide voltage across the resistor element R_1 in response to grid current flow through the input grid circuit. Such grid voltage developed across the resistor R_1 may be utilized for automatic volume control (AVC). The AVC voltage is employed automatically to bias the control grids of the preceding amplifier tubes in a manner well-known to those skilled in the art.

The plate circuit 5 in Fig. 2 has a pass band width of above 30 kc., while the mean frequency has a value of 860 kc. This is appropriate since the effect of the locked-in oscillator network has been to divide the mean frequency of the FM wave energy by a factor of 5, and the overall frequency deviation range has also been divided by the same factor. The pass band width should be sufficiently above 30 kc. to provide suitable operating tolerances. Further, the plate current is substantially constant regardless of amplitude variations at the signal input grid. This effect is secured, as explained in the aforesaid Beers patent, without the use of a special amplitude limiter stage. The advantages of frequency division at this point of the FM receiving system have been explained in the Beers patent. The extension of the lock-in range of the oscillator accomplished by this invention as compared with the arrangements shown in the Beers patent will enable reception of waves which are frequency modulated over a wider range, and will guard against the distortion which might otherwise occur by reason of the aforementioned "break-out" effect. Since the FM wave energy developed across the plate circuit 5 is modulated in strict accordance with the originally received FM waves, save that the mean frequency and extent of frequency deviation have been proportionately reduced, the output of the locked-in oscillator may now be subjected to suitable discrimination and rectification.

The discriminator input circuit employed herein feeds a pair of opposed diode rectifiers 17 and 18. The discriminator network is similar to that disclosed and claimed by J. D. Reid in U. S. Patent No. 2,341,240, granted February 8, 1944. In accordance with my present invention, the design of the discriminator network is rendered substantially independent of the lock-in range of the locked-in oscillator. Further, the circuit has been improved to provide control over the degree of linearity of the detection characteristic. The opposed diodes 17 and 18 will be separately fed with signal energy which has the form of amplitude modulated wave energy by virtue of the action of the discriminator input

circuit which translates FM wave energy into corresponding amplitude modulated carrier wave energy.

Returning, now, to consider the specific construction and operation of the locked-in oscillator circuit, the oscillator grid 6 of tube 1 is connected by lead 6' to the high alternating potential side of tickler coil L_1. The lower end of the coil is connected to ground through the parallel-connected combination of resistor R_3 and condenser C_{10}. Condenser C_2 shunts the tickler coil L_1. The grid circuit 5' is not necessarily resonated to a particular frequency and the capacity of C_2 is not critical. In a practical circuit the resonant frequency of L_1C_2 can be between 1500 and 2000 kc. and the frequency of the tank circuit 5 can be 860 kc.

The screen grid 2' of tube 1 is connected to a source of positive potential +S, say +80 volts, and is bypassed to ground for I. F. currents by condenser C_1. The plate 4 of tube 1 is connected to the +B terminal, say at +90 volts, through the resonant circuit 5. The resonant tank circuit 5 consists of the parallel-connected combination of coil L_2, resistor R_4 and condenser C_4. The resistor element may be made variable, as indicated by the arrow through the resistor, for a reason to be explained at a later point. Coils L_1 and L_2 are magnetically coupled to provide the proper amount of regenerative feedback in order continuously to produce the oscillations at the desired frequency division ratio. Condenser C_5 bypasses the lower end of resistor R_4 to ground for the oscillator current.

The auxiliary resonant network, which has been referred to above, is designated 5'', and consists of the parallel-connected combination of condenser C_3, resistor R_2 and coil L_3. The coil L_3 is magnetically coupled to the plate coil L_4, and this coupling is indicated by the dashed arrow through both coils. The resistor R_2 is preferably variable, as indicated. The degree of coupling between coils L_3 and L_2 predominantly determines the extent of the lock-in range of the oscillator. There are other factors which influence the lock-in range, but these factors are minor compared to the coupling between the aforesaid coils. The auxiliary resonant network 5'' is tuned to the same resonant frequency as the plate circuit 5. For maximum lock-in range the auxiliary coupled circuit 5'' is slightly overcoupled, (closer than critical coupling) with respect to tank circuit 5.

In Fig. 3 I have shown a method of constructing the locked-in oscillator transformer 7 of Fig. 2 so as to show the simplicity of the present arrangement for securing an extended lock-in range. The coils L_1, L_2 and L_3 are all mounted on a hollow coil form 20, which may be of the type generally used in a standard I. F. transformer designed to operate at 455 kc. The coil form is usually made of plastic, phenolic resin, or ceramic material, and is provided at either end with the adjustable comminuted iron cores 21 and 22. These iron cores, as is well known to those skilled in the art, are located within the bore of the form 20, and may be adjusted from either end of the coil form to vary the magnitude of inductance of each of the coils. The coil L_3 is mounted so as to have its inductive magnitude varied by axial adjustments of iron core 21, while the coil L_2 is spaced from the coil L_3. The inductive magnitude of coil L_2 is varied by axially adjusting the iron core 22.

Of course, the sections of both coils L_3 and L_2 will be so spaced as to provide the desired degree of coupling referred to above. The oscillator tank coil L_2 may be composed of three pies, or sections, in series-aiding connection. The tickler coil L_1 may be formed of two pies, one on each side of coil L_2, connected in series-relation. This is done to give fairly tight coupling without increasing the inductance value of coil L_1 beyond the allowable limits. Of course, the coil L_3 is, therefore, coupled to the tickler coil L_1 as well. This coil design is shown merely as an example, and the invention is in no way limited to this design.

If the effective coupling between coils L_3 and L_2 is gradually increased from some low value by moving coil L_3 closer to L_2, the oscillator lock-in range will increase uniformly. However, this increase will reach a point eventually where the oscillator begins to give a distorted output in the middle of the lock-in range. Further increase in coupling will cause the oscillator to "break-out" in the middle of the range, but not at the ends. This provides a simple means for adjusting the lock-in range. The same result can be obtained by means of the variable resistance R_2, since a decrease in the "Q" of coil L_3 is equivalent to a decrease in coupling between L_3 and L_2. Loading a transformer with resistors decreases the effective coupling between the windings of the transformer, and, therefore, adjustment of the magnitude of either of the shunt resistors R_2 or R_4 will provide a control over the lock-in range.

In Fig. 4 I have graphically portrayed response curves for the tank circuit of the locked-in oscillator. The single-peaked curve *a* shows the type of response curve secured when the auxiliary network 5'' is removed from the system, or when the coupling between coils L_3 and L_2 is so small that the auxiliary circuit does not affect the response curve. Fig. 5 shows the corresponding phase angle characteristic of the plate voltage with respect to the plate current. In Fig. 5 the solid line curve *a'* is the phase angle characteristic corresponding to the response curve *a* of Fig. 4. It will be noted that the phase angle is zero at one point only, to wit: the frequency F_c.

On the other hand when the auxiliary network 5'' is inserted into the system, and is coupled to the plate circuit to a degree sufficient to provide the dashed line double-peaked curve *b* of Fig. 4, there results the phase-angle characteristic *b'* depicted in Fig. 5. It will be seen that the dashed line curve *b'* has a considerable extent of nearly zero phase angle as the frequency is varied. The reactive plate current which must be supplied by the tube to lock in the oscillator is, therefore, small over a considerable frequency range. In other words, the phase angle of the tank circuit impedance is nearly zero over a considerable range of frequencies. This means that the circuit is almost resonant throughout this range, and a small amount of reactive current from the tube can cancel the slight reactance of the circuit to produce lock-in, thereby effecting a corresponding increase in the extent or range of lock-in.

I have found that it is possible to secure a lock-in range, through all prior radio frequency and I. F. selectivity, of ±130 kc. or more. To adjust the locked-in oscillator circuit, the tank circuit 5 is tuned by adjusting core 22 until the oscillator locks in with an incoming frequency modulated signal from a signal generator. The latter may feed the signal into the I. F. channel at 4.3 mc. The modulation is then removed from the carrier wave generated by the signal generator, leaving the carrier at 4.3 mc. The FM detector is then adjusted to zero balance by connecting a high-resistance voltmeter from either end of resistor R_8 to ground, and adjusting the inductance of the input coil L_4 until there is no voltage from the output of the detector to ground. The coil L_2 is then adjusted until the lock-in range is approximately symmetrical about frequency F_c. Coil L_3 is then adjusted until circuit 5'' is tuned to the same frequency as 5. The lock-in range can be adjusted to the desired amount by either shifting the position of coil L_3 with respect to L_2, or by adjusting either resistor R_2 or R_4. A slight readjustment of coil L_2 may be necessary for best results.

The curves of Fig. 4 and Fig 5 refer to the tank circuit only, as seen by the plate of the tube. When the tube is added the curves for the tube plus the tank circuit differ from those shown, since the tube develops an equivalent shunt capacitance or inductance, in accordance with Figs. 1*a*, *b*, *c*, which locks in the oscillator. My invention extends this lock-in range.

An ordinary volume control resistor can be used for either of resistors R_2 or R_4, and will give a smooth control of the lock-in range of the oscillator. Hence, this provides a simple means for obtaining adjustable selectivity in an FM receiver, since varying the lock-in range results in variable selectivity. This property of the locked-in oscillator is described in the aforementioned Beers patent. This variable selectivity, or variable lock-in range, may also be secured by providing ready adjustment of coil L_3 with respect to L_2. On the other hand, there could be provided an iron core that couples the two coils simultaneously. In addition, it is within the scope of my invention to provide either separate or concomitant adjustment of the resistance values of resistors R_2 and R_4 and the coupling between coils L_3 and L_2.

The maximum lock-in range occurs when coils L_2 and L_3 are slightly overcoupled. The dashed line curve b of Fig. 4 indicates this condition of slight overcoupling. It can be shown that for maximum lock-in range the product $Q_m k$ 1.1, where Q_m is the geometrical mean of the Q of each of coils L_3 and L_2 defined by $Q_m^2 = Q_2 Q_3$, and k is the coefficient of coupling between the coils defined by

$$k = \frac{M_{2-3}}{L_2 L_3}$$

where M_{2-3} is the mutual inductance between L_2 and L_3. The lock-in range decreases uniformly as this product decreases from 1.1 towards zero. Hence, this explains why variation of any of the three aforementioned components provides a control over the lock-in range.

Turning now to the FM detector I utilize a simplified discriminator input circuit, and it is not necessary to design the discriminator input circuit with any consideration for the extent of the lock-in range. This is obvious from what has preceded. The discriminator input circuit consists of the parallel-connected combination of coil L_4, resistor R_5 and condenser C_7. The upper end of the combination of elements is connected to the anode 30 of diode 17, while the lower end of the combination is connected to the anode 31

of the opposed diode 18. The high potential side of plate circuit 5 is coupled to the anode 30 by condenser C_6. The cathode 32 and cathode 33 of diodes 17 and 18 respectively are connected by condenser C_8, and the cathode 33 is grounded. The resistor R_8 is connected to the cathode 32, and is connected by the output lead to the following audio frequency amplifier (not shown). A further condenser 29 may shunt resistor R_8 and condenser C_8 to de-accentuate the high audio frequencies.

The load resistor R_6 is connected directly in shunt with the space current path of diode 17 between the anode 30 and cathode 32. The load resistor R_7 is connected similarly directly between anode 31 and cathode 33. This manner of connecting the load resistors of the detector circuit differs from that shown in the aforesaid Reid patent, and provides simplification of the detector circuit. In general, the present FM detector circuit functions in the manner described in detail in the aforesaid Reid patent, and it is not necessary to go into detail with regard to such operation. It is believed sufficient for the purposes of the present application to explain that the tuned input, or discriminator, section 40, together with the inherent capacity of diode 18, functions to provide the discrimination action.

In Fig. 6 I have depicted a typical detection characteristic for the type of detector shown in Fig. 2. The frequencies F_1 and F_2 denote the opposite peak limiting frequencies. The resultant instantaneous output voltage of the detector is zero at the frequency F_c. It is highly desirable, of course, that the curve be highly linear between the peak limiting frequencies. The detector circuit shown in Fig. 2 possesses such a characteristic, particularly when the input circuit 40 is connected directly in shunt across the oscillator plate circuit 5. Hence, the discriminator is highly desirable when used in connection with an FM receiver of the type shown in Fig. 2. The resonant circuit 40 is tuned to a frequency such that it possesses a parallel resonance near one of the peak limiting frequencies, F_2 of Fig. 6, while it is series resonant with the inherent anode to cathode capacity of diode 18 at the other limiting frequency F_1.

The resistor R_6 is effectively in shunt with the entire circuit and controls the parallel "Q" of the discriminator circuit, while the resistor R_7 is effectively in shunt with the capacity of diode 18 and controls the effective series "Q" of the discriminator circuit. For optimum linearity these two Q's should be approximately equal, and, therefore, the resistive magnitude of resistor R_7 will not necessarily equal that of resistor R_8. It is highly desirable that the detection characteristic be linear between peak limiting frequencies as far apart as 30 kc., since that is the normal pass band required to be handled. Moreover, it is expected that the lock-in range shall be ±130 kc. or more, and the frequency spacing betwen the limiting frequencies F_1 and F_2 should be substantially greater than one-fifth of the over-all lock-in range of the locked-in oscillator for a five-to-one division ratio.

Each of the opposed rectifiers 17 and 18 includes in circuit therewith its respective load resistor. At the instant when the applied signal energy has the mean frequency value F_c, the rectified voltages across the resistors R_6 and R_7 are equal in magnitude and opposite in polarity.

Hence, the resultant potential at the cathode end of resistor R_6 is zero. On the other hand, the potential at the cathode end of resistor R_8 will vary in magnitude and polarity depending respectively upon the extent and direction of frequency deviation with respect to the mean frequency. Accordingly, the voltage taken off from the series-connected output loads of the opposed rectifiers 17 and 18 corresponds to the original modulation signal voltage applied to the carrier at the FM transmitter.

The resistor R_8 and the condenser 29 to ground provides a de-emphasis network whose function is well known in the art of frequency modulation reception. Briefly, the de-emphasis network acts to diminish the response at the higher audio frequencies, since during transmission of the FM waves such higher audio frequency components may have been disproportionately emphasized.

The following list of illustrative circuit constants is supplied for a practical embodiment of the circuit shown in Fig. 2.

Diodes 17, 18=6H6 tube
R_1=22,000 ohms
R_2=250,000 ohms (maximum value)
R_3=20,000 ohms
R_4=500,000 ohms (maximum value)
R_5=100,000 ohms
R_6=100,000 ohms
R_7=250,000 ohms
R_8=100,000 ohms
C_1=0.1 microfarad (mfd.)
C_2=47 micro-microfarads (mmf.)
C_3=27 mmf.
C_4=33 mmf.
C_5=0.1 mfd.
C_6=33 mmf.
C_7=22 mmf.
C_8=56 mmf.
C_9=220 mmf.
C_{10}=400 mmf.
L_1=0.20 millihenry (mh.)
L_2=0.46 mh.
L_3=1.00 mh.
L_4=0.96 mh.

Mutual inductance between coils L_1 and L_2=0.20 mh.

The frequency discriminator described in Fig. 2 is a very desirable circuit for use with my invention, but it is not essential to the operation of the locked-in oscillator. Other circuits can be employed to give satisfactory results. For example, either of the detectors of the type shown in the aforesaid Beers patent may be used. Likewise, the circuit shown by S. W. Seeley in U. S. Patent No. 2,121,103 granted June 21, 1938, or the one disclosed by Conrad in U. S. Patent No. 2,057,640 granted October 13, 1936, may be employed. Furthermore, the discriminator input circuit need not necessarily be of the balanced type, but may consist of a single tuned circuit so adjusted that the center frequency of the output from the locked-in oscillator falls in the middle portion of the nearly straight portion, on either side of the resonance curve.

The discriminator input circuit of Fig. 2 can, also, be modified to operate with a single diode as shown by Fig. 7. The resistor 35 in series with condenser C_6 is used to decrease the detuning effect of the discriminator circuit on the locked-in oscillator. Capacitor 36 is chosen so as to be equivalent to the anode to cathode capacity of omitted diode 18 of Fig. 2. The capacitor 36 is connected from the low potential side of circuit

40 to ground. The rectified signal voltage is taken off across load resistor R_6. The audio signal output connection including resistor R_8 is made to the anode end of the load resistor. The discriminator circuit 40, 36 functions in the same manner as described in connection with the discriminator circuit of Fig. 2.

While I have indicated and described several systems for carrying my invention into effect, it will be apparent to one skilled in the art that my invention is by no means limited to the particular organizations shown and described, but that many modifications may be made without departing from the scope of my invention.

What I claim is:

1. In combination with a tube provided with at least an electron emitter, a control element, a grid and output electrode, means for applying to the control element frequency modulated input current of a desired carrier frequency, a resonant tank circuit reactively coupling said grid and output electrode and tuned to a desired subharmonic frequency of the input frequency, a resonant network magnetically coupled with the tank circuit, said network having its frequency equal to the subharmonic frequency, and said coupling being adjusted to provide a relatively wide lock-in range for subharmonic frequency oscillations.

2. In combination with a locked-in oscillator tube provided with at least an electron emitter, a control element, an oscillator grid and oscillator output electrode, means for applying to the control element high frequency current which is frequency modulated and has a desired mean frequency, a resonant tank circuit coupling said oscillator grid and output electrode and tuned normally to a desired subharmonic frequency of said mean frequency, a selective network tuned to a frequency equal to said subharmonic frequency, said selective network comprising inductance, capacity and resistance in shunt relation, means coupling said selective network to said tank circuit to a degree sufficient to substantially extend the lock-in range, and means for varying the magnitude of said resistance thereby to control the effective degree of coupling to the tank circuit and hence the lock-in range.

3. In combination with a locked-in oscillator tube provided with at least an electron emitter, a control element, an oscillator grid and oscillator output electrode, means for applying to the control element high frequency current which is angle modulated and has a desired mean frequency, a resonant tank circuit reactively coupling said oscillator grid and output electrode and tuned normally to a desired subharmonic frequency of said mean frequency, a selective network tuned to a frequency substantially equal to said subharmonic frequency, means coupling said selective network to said tank circuit, and means for varying the "Q" of the tank circuit to control the degree of the last-mentioned coupling and hence the lock-in range.

4. In combination, a locked-in oscillator tube provided with at least an electron emitter, a control element, an oscillator grid and oscillator output electrode, means for applying to the control element high frequency current which is angle modulated and has a desired mean frequency, a resonant tank circuit reactively coupling said oscillator grid and output electrode and tuned normally to a desired subharmonic frequency of said mean frequency, and the improvement comprising a selective network tuned to a frequency substantially equal to said subharmonic frequency, means coupling said selective network magnetically to said tank circuit, and means for varying the mutual inductance between the tank circuit coil and a coil in the seelctive network to control the lock-in range.

5. In combination, a locked-in oscillator tube provided with at least an electron emitter, a control element, an oscillator grid and oscillator output electrode, means for applying to the control element high frequency current which is angle modulated and has a desired mean frequency, a resonant tank circuit reactively coupling said oscillator grid and output electrode and tuned normally to a desired subharmonic frequency of said mean frequency, the improvement comprising a selective network consisting of inductance, capacitance and resistance in series which is tuned to a frequency substantially equal to said subharmonic frequency, means coupling said selective network to said tank circuit, and means for varying the resistance of said selective network to control the degree of coupling and hence the lock-in range.

6. In combination with a locked-in oscillator tube provided with at least an electron emitter, a control element, an oscillator grid and oscillator output electrode, means for applying to the control element high frequency current which is angle modulated and has a desired mean frequency, a resonant tank circuit reactively coupling said oscillator grid and output electrode and tuned normally to a desired subharmonic frequency of said mean frequency, a selective network tuned to a frequency substantially equal to said subharmonic frequency, means coupling said selective network to said tank circuit to increase the lock-in range, detection means in shunt with said tank circuit which is linear and substantially without effect on the lock-in range, and means for adjusting the "Q's" of said tank circuit and said selective network separately to give continuous variation of the lock-in range whereby the lock-in range can be restricted to include the whole of the range of frequencies of the desired modulated wave but not enough to include frequencies substantially outside of said last-mentioned range, so that interference due to noise frequencies or adjacent-channel frequencies is reduced.

MURLAN S. CORRINGTON.

REFERENCES CITED

The following references are of record in the file of this patent:

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Number	Name	Date
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