Aug. 16, 1932. L. J. WOLF 1,872,379

FREQUENCY CHANGER

Filed Dec. 9, 1927

Fig.1.

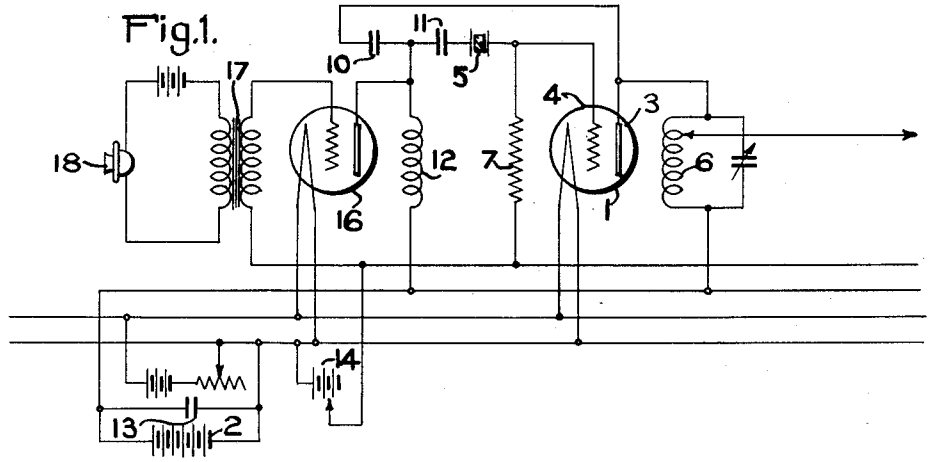



Fig. 2.

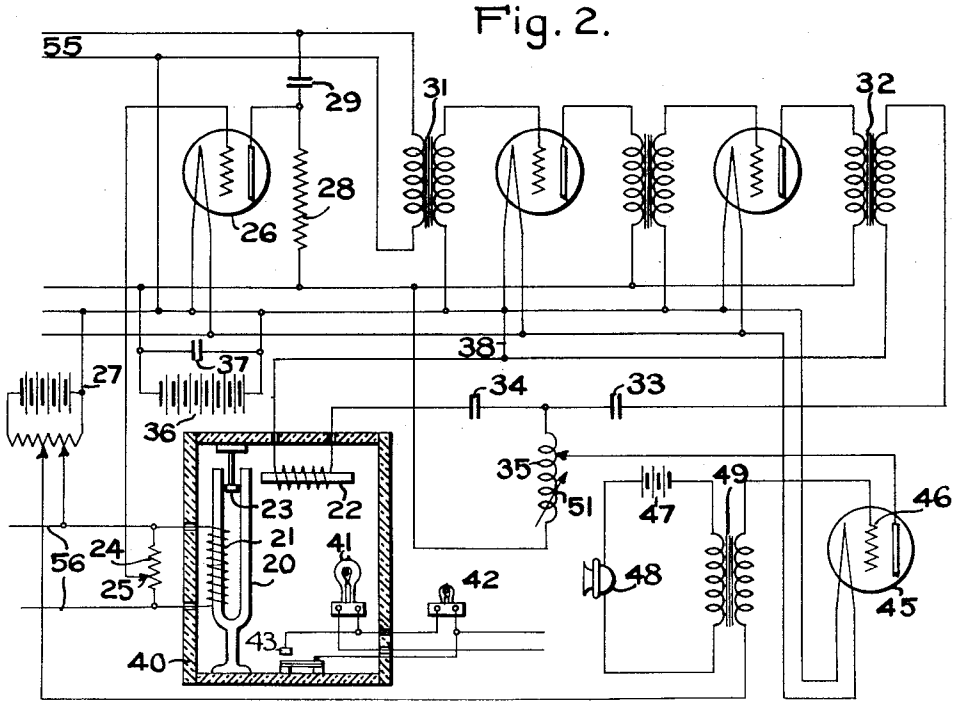
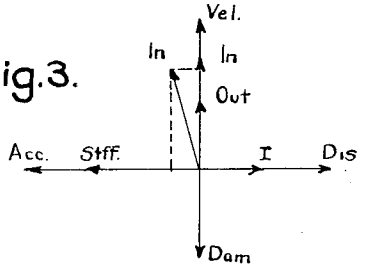



Fig.3.




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# UNITED STATES PATENT OFFICE

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## FREQUENCY CHANGER

Application filed December 9, 1927. Serial No. 238,824.

This invention relates to frequency standards and particularly to electrical systems in which a tuning fork, a piezo-electric crystal or any other device having a characteristic frequency of mechanical vibration is used in connection with electrical circuits to establish a definite frequency therein.

It is an object of this invention to provide, in conjunction with a mechanical or electro-mechanical device maintained in oscillation by a regenerative circuit, a means for adjusting the frequency of the system.

It is a further object of this invention to provide adjusting means for the system just mentioned in which the adjustment may be performed so rapidly that it can serve as a means of frequency modulation for the transmission of audible signals.

It is a further object of this invention to provide for an adjustment of the frequency without introducing tuned circuits with their consequent tendency to instability.

Other objects of the invention and details of the construction will be apparent from the following description and the accompanying drawing, in which,

Figure 1 is a diagram illustrating the application of my invention to a system using a piezo-electric crystal.

Fig. 2 is a similar diagram illustrating the application thereof to a tuning fork, and

Fig. 3 is a vector diagram to which reference will be made for explaining the theory of operation.

Piezo-electric crystals, tuning forks and other devices having characteristic mechanical frequencies of vibration have been used in connection with radio signalling for the production of high frequency currents of very constant frequency. The mechanically vibrating device is thus made to serve as a frequency standard.

It was at first believed that only such conditions as directly affected the mechanical properties of the mechanically vibrating body, such as temperature, could produce an effect upon the frequency of the system. It has recently been discovered that if the tuning of the circuits associated with the mechanical device be slightly different from the frequency of mechanical resonance, the system can be caused to vibrate at a frequency somewhat different from that of the free mechanical vibration of the frequency standard.

It has also been discovered that the frequency of the resulting electrical oscillations can be altered to a small degree by altering certain adjustments of the electrical system, for example, by altering the electromotive force impressed upon the plate circuit of a vacuum-tube oscillator.

Attempts to control the frequency of the generated electrical oscillations by altering the temperature of the vibrating body have proved cumbersome and only partially reliable. Attempts to alter the frequency of the generated electrical oscillations by altering either the tuning of certain electrical circuits, or the magnitude of certain electromotive forces have caused unstable conditions which frequently give rise to abrupt and undesired changes in frequency.

I have discovered that if, in a regenerative system including a tuning fork, a piezo-electric crystal or any other device intended to fix the frequency of the system by its own mechanical frequency, the phase relation between the output and the regenerative energy be altered, the frequency can be thereby altered. This method is not effective for compelling the mechanically resonant device to oscillate at a frequency widely different from its natural period, but departures, amounting to a few per cent of the natural frequency, can be produced in this way.

It is an object of my invention to provide a phase-changing device between the connections to which the mechanically vibrating device delivers energy and the connections from which regenerating energy is delivered to said mechanically vibrating device.

It is a further object of my invention to provide for the adjustment of said phase-changing device.

It is a further object of my invention to produce said adjustment by response to sound.

It is a further object of my invention to adjust the frequency of a system including a mechanically oscillating device and a re-

generative circuit arrangement without changing the tuning of any resonant circuit so located in said arrangement that it can render the system unstable.

Other objects of my invention will be evident from the following detailed description which taken with the accompanying drawing will make the details of construction clear.

In the accompanying drawing, the vacuum tube 1, in Fig. 1, is supplied with energy from the plate battery 2 and has a regenerative coupling connection between the plate 3 and the grid 4 through a piezo-electric crystal 5. The tuned circuit 6 and the grid leak 7 are familiar features of a regenerative vacuum-tube oscillator.

A phase-changing device is inserted in the feed-back coupling. This includes two condensers 10 and 11 in series in the connection between the plate 3 and that electrode of the crystal 5 which is most remote from the grid 4. It also includes an inductor 12, one extremity of which is connected between the condenser 10 and 11 and the other extremity to the filament of the tube 1. The connection to the filament is, in the form illustrated, through the plate battery 2, or rather through the condenser 13 which shunts said plate battery.

A C-battery 14 is connected to the terminal of the grid leak 7 opposite the grid 4. It will be noted that the electrode of the crystal 5 connected to the grid 4 is connected to the opposite electrode by a path including the resistor 7, the C-battery 14, the battery 2 and condenser 13 in parallel and the inductor 12 and condenser 11, in series.

A part or the whole of the inductor 12 is shunted by the plate-filament space of a vacuum tube 16. The grid of the tube 16 is connected to the C-battery 14 through the secondary of a transformer 17, the primary of which is energized by current from the microphone 18.

In Fig. 2, similar connections are shown associated with a tuning fork 20, which is analogous to the piezo-electric crystal 5. One tine of the tuning fork is surrounded by a coil 21, and the other tine is adjacent to one pole of a magnet 22. Between the two tines, a body 23 of magnetic material is supported.

A potentiometer including a resistor 24 and an adjustable contact 25 is connected across the terminals of the coil 21. The adjustable contact of the potentiometer is connected to the grid of a vacuum tube 26 and one extremity of the resistor 24 is connected through a grid-biasing device 27 to the filament of the tube 26. The grid of the tube 26 is thus exposed to the steady biasing potential and the varying potential in a portion of the resistor 24.

The output of the tube 26 is coupled by means of a resistor 28 and a condenser 29 to the input transformer 31 of an amplifier. As illustrated, the amplifier is of several stages but the principle is the same if only a single stage is used, or if the amplifying action of the tube 26 alone be relied upon.

A transformer 32 delivers the output of the amplifier to the magnet 22. The connection over which this delivery is made includes two condensers 33 and 34 in series, and an inductor 35. One extremity of the inductor 35 is connected between the two condensers 33 and 34 and the other extremity is connected through the B-battery 36 and the condenser 37 in parallel thereto, to the filament of the tubes. The filaments are connected, as shown at 38, to that side of the line from the transformer 32 opposite the condensers 33 and 34.

The tuning fork 20 is enclosed in a thermally insulating housing 40, for example, a wooden box. This box is maintained at a temperature somewhat above that of the surroundings by means of a heating lamp 41 which is in series with an indicator lamp 42. A connection controlled by a thermostat 43 is in shunt with the lamp 41.

When the connections through the thermostat are closed, the lamp 41 is strongly energized and heats the interior of the box 40. The lamp 42, under these conditions, will be dimly lighted. When the thermostat 43 opens its contacts, the lamp 41 will receive less current and less heat will be delivered from it to the interior of the box.

The observer is able to know conditions in the box by observing the light 42. If this light is bright, the lamp 41 is heating the box but slightly. If the light 42 is dim, the lamp 41 is heating the box strongly. If the lamp 42 is out, the connections are broken.

All or a portion of the inductor 35 is shunted by the plate-filament space in a tube 45. The impedance of the plate-filament space in this tube is controlled by the grid 46, the potential of which is controlled by the adjustable grid-biasing device 27. The microphone 48 acting through the usual battery 47 and transformer 49 imposes a varying potential on the grid 46 in addition to the potential from the battery 27.

The connection from the plate of the tube 45 to the inductor 35 is adjustable and in addition the inductor itself is adjustable. The latter adjustment is indicated at 51.

In the operation of the device, as illustrated in Fig. 1, a constant potential is maintained across the capacity consisting of the condenser 11 and piezo-electric crystal 5, in series. This potential is supplied by the B-battery 2 and the C-battery 14, in series.

The variations in potential which occur at the plate 3 are impressed through the filter comprising condensers 10 and 11 and inductor 12 upon the left-hand electrode of the

crystal 5. Variations of potential at the plate 3 also affect the right-hand electrode of the crystal directly over the grid-plate capacity of the tube 1.

The filter, by introducing a phase-change in the path exterior to the tube 1 which is not introduced in the path through the interior capacity, ensures a difference of potential between the electrodes of the crystal by which it is maintained in oscillation and the natural frequency of this oscillation would, normally, fix the frequency of the current delivered by the tube 1.

The circuit 6 is tuned to approximately this frequency and thus ensures that the potential changes on the plate 3 will be large and that, therefore, the feedback action through the crystal 5 will be sufficient to maintain the system in oscillation. The leakage from the grid 4 over the grid leak 7 will regulate the average or steady value of the bias on the grid 4 and thus the magnitude of the oscillations is established.

Preferably the filter comprising condensers 10 and 11 and inductor 12 is so designed that its cut-off frequency is nearly equal to the natural frequency of the crystal 5. Such a filter has a phase-changing characteristic which is nearly constant from high frequency to the cutoff frequency of the filter, changes rapidly with changing frequency in the neighborhood of the cut-off frequency, and then assumes a constant but different value for lower frequencies.

In the neighborhood of the cut-off frequency, a very small change in the frequency of the oscillations in the system will result in very large changes in the phase difference between the potential delivered by the plate 3 to the filter and the potential delivered by the filter to the crystal. Conversely, a very small change in the cut-off frequency will result in a very large change in said phase difference.

I have found that by changing this phase difference I can control the frequency of the oscillations in the system. The change which I can thus introduce enables me to produce in such a system, frequencies which differ by several percent from the natural frequency of the crystal 5.

The most convenient way of adjusting the cut-off frequency and so the phase change introduced by the filter, is to shunt the inductor 12 or a portion of it by a variable impedance. As illustrated in Fig. 1, the impedance of the tube 16 is in shunt to the inductor 12 and the value of this impedance is varied either by adjusting the C-battery 14 or by speaking into the microphone 18.

Various applications of this principle are possible. In Fig. 1 I have illustrated it as applied to the problem of changing the frequency of a broadcasted radio frequency wave in accordance with an audible signal. When the microphone 18 receives sound, the frequency of the oscillations generated in the system, including the circuit 6, is altered. The frequency delivered by the circuit 6 to whatever apparatus is connected at the right of Fig. 1 is altered in the same way. This connection may extend directly, to a conventional master oscillator transmitting system, or may extend through a series of frequency multipliers to a transmitting system.

In the form illustrated in Fig. 2, instead of a piezo-electric crystal, a tuning fork is used. If this fork be set into vibration, when the tines approach each other, the magnetic circuit through the fork and the body 23 will be of smaller reluctance, because the air gaps are shorter. The flux through the coil 21 will thus be changed. When the tines recede from each other, the flux in the coil 21 will be changed in the opposite direction.

The changes in flux in the coil 21 induce electromotive forces therein which cause a current in the resistor 24. The adjustable contact 25 causes a portion of the drop over the resistor 24 to be impressed upon the grid of the tube 26.

Preferably, the bias from the device 27 is of such value that the tube 26 will act as an amplifying tube. The potential changes induced in the coil 21 are amplified by the tube 26 and conveyed by the condenser 29 to the primary of the transformer 31. The terminal of this primary opposite that connected to the condenser 29 is connected to the filament of the tube 26.

The transformer 31 thus produces a potential on the grid of the first tube of the amplifier which varies in accordance with the movement of the fork 20. The impulses from the fork are magnified by the action of the amplifier and produce currents in the winding of the magnet 22 which have the same frequency as the electromotive force induced in the coil 21, that is, they have the same frequency as the fork.

The phase of the currents in the magnet 22 is adjustable. The adjustment is secured by the filter, including condensers 33 and 34, in series in one side of the line from the transformer 32 to the magnet 22, and the inductor 35, in shunt to said line. The shunt including the inductor 35 is from that side of the line including the condensers through the inductor 35, the battery 36 and condenser 37 in parallel, and through the connection 38 to the other side of the line.

The natural frequency of the fork 20 and the cut-off frequency of the filter are preferably nearly equal. Consequently, the difference in phase between the electromotive force impressed upon the filter by the transformer 32 and the current in the magnet 22 will change rapidly with changes in the value of the inductance 35. This value may be changed by adjusting the inductance itself,

as indicated at 51. In this way, the frequency of the system including the fork 20 may be brought very near to the prescribed frequency.

A still closer adjustment may be made by adjusting the potential from the device 27, which controls the average potential of the grid 46. By the adjustment of the frequency of the system sufficiently close to a standard frequency, the system may be rendered responsive to stimuli of the standard frequency impressed upon the system from without. For example, if over the leads 55 shown at the upper left-hand corner of Fig. 2, an electromotive force of very nearly the frequency to which the fork has been adjusted be impressed, this electromotive force will cooperate with the electromotive force introduced through the condenser 29, and the fork 31 will be subject to two forces of nearly the same frequency.

If the degree of regeneration is within certain limits, the frequency impressed over the line 55 will be adopted by the fork instead of the frequency determined by the constants of the fork and the characteristics of the filter. This is convenient when the fork is used as explained in my copending application, Serial No. 238,823, filed December 9, 1927, and assigned to the Westinghouse Electric and Manufacturing Company, for maintaining two broadcasting stations at the same frequency.

Again, as explained in connection with Fig. 1, the microphone 48 by changing the character of the filter may cause corresponding changes in the output of a transmitting station. For this purpose, the leads 56, shown as extending toward the left in Fig. 2, are connected to frequency multiplying devices which control the transmitting device of a broadcasting station.

Although I have illustrated the phase-changing device by which I control the frequency as a high-pass filter, any device which produces an adjustable change in phase relation between the output of the fork, that is, the electromotive force delivered by the coil 21 and the input to the fork, that is, the force exerted by the magnet 22, can be made to produce the frequency changes.

Similarly, any mechanically oscillating system, such as a fork, the pendulum of a clock, a piezo-electric crystal, etc., if it be regenerated, that is if its output be connected through an amplifier to its input, will not only maintain a frequency approximately that of the mechanical resonance of the fork, pendulum or the like, but can have its frequency adjusted, by adjusting the phase of the feed-back which produces the regeneration.

The principle on which the control of frequency is dependent may be seen by a consideration of Fig. 3. In this figure, certain rotating vectors are illustrated to indicate the various elements of the movement and others to indicate the several forces acting.

The vector marked Dis represents the displacement. In the case of the fork, this is the distance of the tines from their stationary position. The vector marked Vel represents the velocity. In case of the fork, this is the velocity of the tines. In the case of the piezo-crystal, it is the velocity at which the crystal is shrinking or expanding. The vector marked Acc represents the acceleration of the vibrating body.

In any mechanical vibrating system, the damping is a force, the phase of which is opposite to that of the velocity. This is represented in Fig. 3 by the vector marked Dam. It is without influence upon the frequency because it has no component at any angle to the velocity.

A vector opposite in phase to the displacement and marked Stff represents the restoring force usually known as the stiffness, because it tends to restore the system to its stationary position. A vector opposed to the acceleration shown at I represents the inertia.

The stiffness and the inertia have a marked influence upon the frequency of the system, but the damping, has, as already pointed out, little or no influence thereon.

The vector marked Out represents the output, that is, the energy delivered to the amplifier. In the case of the fork, it is nearly in phase with the velocity.

It is therefore shown in this direction in the diagram. If there were no phase-changing device introduced in the amplifier, or its connections, the input would be in phase with the output and therefore be like the vector In.

In order to see the effect of a phase change, I have assumed that the vector In, instead of being in the position illustrated is in the position In'.

The vector in the position In is at right angles to the acceleration. This represents the steady condition when no phase difference exists. The vector In' has a component in the direction of the acceleration. It tends, therefore, to increase the energy in the system, which must result in larger velocities. This component, moreover, is also in the direction of the stiffness reaction. It tends to increase the stiffness of the mechanical system, that is, to produce a greater resistance to displacement, and, therefore, to lessen the displacement.

The consequence of the position In' for the vector representing the driving force is, therefore, to increase the velocity and to diminish the displacement. Obviously, a greater velocity producing movement through a smaller displacement will accomplish that displacement sooner, that is, the frequency of the vibrating system is increased.

Another and perhaps clearer way of showing why the change in phase relation will cause a change in frequency is as follows: the horizontal component of the vector In′ tends to increase the stiffness and decrease the inertia. The stiffness and inertia together control the natural frequency of any vibrating system. To increase the stiffness and diminish the mass will result in a higher natural frequency.

It will be noted that in each of these explanations, no attention has been paid to the vertical component of the vector In′. This vertical component is opposite to the damping. It will therefore be effective in altering, not the frequency, but the amplitude of the vibrations. The amplitude will always increase until the losses represented by the damping vector and the input energy represented by the vertical component of In′, are equal.

Many other mechanically vibrating systems beside the pendulum, the tuning fork and the piezo-electric crystal specifically mentioned herein, are known to workers in the art, and the control of their frequency by the system here described is within the spirit of this invention.

Many other modifications will be evident to those skilled in the art and the specific mention of only a few herein is not to be interpreted as a limitation, no limitation being intended except that required by the prior art or expressed in the claims.

I claim as my invention:

1. In an oscillation system, a device having a natural period of mechanical vibration and means for producing an electromotive force in accordance with the vibratory movement thereof, an amplifier to which said electromotive force is delivered, means for impressing a force derived from the output of said amplifier upon said device to tend to counter-act the damping of said movement and means for controlling the phase relation between said electromotive force and said impressed force.

2. In an oscillation system for transmitting signals by frequency modulation, a device having a natural period of mechanical vibration and means for producing an electromotive force in accordance with the vibratory movement thereof, an amplifier to which said electromotive force is delivered, means for impressing a force derived from the output of said amplifier upon said device to tend to counter-act the damping of said movement and means for controlling the phase relation between said electromotive force and said impressed force in accordance with said signals.

3. In an oscillation system, a device having a natural period of mechanical vibration and means for producing an electromotive force in accordance with the vibratory movement thereof, an amplifier to which said electromotive force is delivered, means for impressing a force derived from the output of said amplifier upon said device to tend to counter-act the damping of said movement, a coupling between said device and one side of said amplifier and signal-controlled means cooperating with said coupling to alter the effect of said coupling upon the phase in accordance with the signal.

4. In combination, a mechanical vibratory device having a well marked tendency to vibrate at one period, means for deriving a periodic potential from the vibration of said device, means including an amplifier for impressing a periodic driving force on said device in accordance with said potential and means for altering the frequency of said device by adjusting the phase of said force.

5. A regenerative system including an amplifier and means for impressing a portion of the output of said amplifier upon the input thereof, said means including a phase changing device and a device having mechanical resonance, said phase changing device comprising a high-pass filter having a cut-off frequency nearly equal to the frequency of said mechanical resonance.

6. A regenerative system including an amplifier and means for impressing a portion of the output of said amplifier upon the input thereof, said means including a phase changing device and a device having mechanical resonance, said phase changing device comprising a high-pass filter having a cut-off frequency nearly equal to the frequency of said mechanical resonance, and means for adjusting the cut-off frequency of said filter.

7. A regenerative system including an amplifier and means for impressing a portion of the output of said amplifier upon the input thereof, said means including a phase changing device and a device having mechanical resonance, said phase changing device comprising a high-pass filter having a cut-off frequency nearly equal to the frequency of said mechanical resonance and means for normally adjusting the cut-off frequency of said filter, through frequency intervals as great as one-tenth of one percent and signal-controlled means for adjusting said cut-off frequency through smaller frequency intervals.

8. In an oscillation system, a tuning fork having a natural period of mechanical vibration and means for producing an electromotive force in accordance with the vibratory movement thereof, an amplifier to which said electromotive force is delivered, means for impressing a force derived from the output of said amplifier upon said tuning fork to tend to counter-act the damping of said movement and means for controlling the phase relation between said electromotive force and said impressed force.

9. In an oscillation system, a device having a natural period of mechanical vibration and means for producing an electromotive force in accordance with the vibratory movement thereof, an amplifier to which said electromotive force is delivered, means for impressing a force derived from the output of said amplifier upon said device to tend to counter-act the damping of said movement and means comprising a section of a band-pass filter for controlling the phase relation between said electromotive force and said impressed force.

10. In an oscillation system, a device having a natural period of mechanical vibration and means for producing an electromotive force in accordance with the vibratory movement thereof, an amplifier to which said electromotive force is delivered, means for impressing a force derived from the output of said amplifier upon said device to tend to counter-act the damping of said movement and means comprising a band-pass filter section having capacity and inductance units for controlling the phase relation between said electromotive force and said impressed force, said means including a vacuum tube having a cathode, a plate, and a control electrode and having its plate-cathode impedance connected across at least a portion of said inductance unit and its control electrode connected to a source of modulating voltage.

11. In a system for generating a frequency modulated carrier wave, an oscillator tube having a cathode, a grid and a plate, an amplifier tube having a cathode, a grid and a plate, a high-pass filter section comprising an inductance coil and two condensers connected in the form of a T, and a piezo-electric crystal connected to the input of said oscillator tube, said inductance coil being connected in the plate circuit of said amplifier tube, one of said condensers connecting the plate of one tube to the plate of the other tube, and the other of said condensers connecting the plate of said amplifier tube to said piezo-electric crystal.

12. The method of signalling with a frequency-modulated carrier wave generated by a means for generating alternating current energy which embodies a mechanically resonant system, said method comprising regeneratively counter-acting the damping of said system, altering the phase of the regeneration in response to signals whereby said alternating current energy is frequency-modulated, and impressing the resulting frequency-modulated carrier wave upon an output circuit.

13. In a system having means for generating alternating-current energy, said means including a mechanically resonant system, the method of transmitting signals by frequency modulation which comprises regeneratively counteracting the damping of said system, altering the phase of the regeneration in response to said signals whereby said alternating current energy is frequency modu'ated, and impressing said modulated energy upon an output circuit.

In testimony whereof, I have hereunto subscribed my name this 21st day of November, 1927.

LESTER J. WOLF.