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ELECTRICAL APPARATUS

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Fig. 1

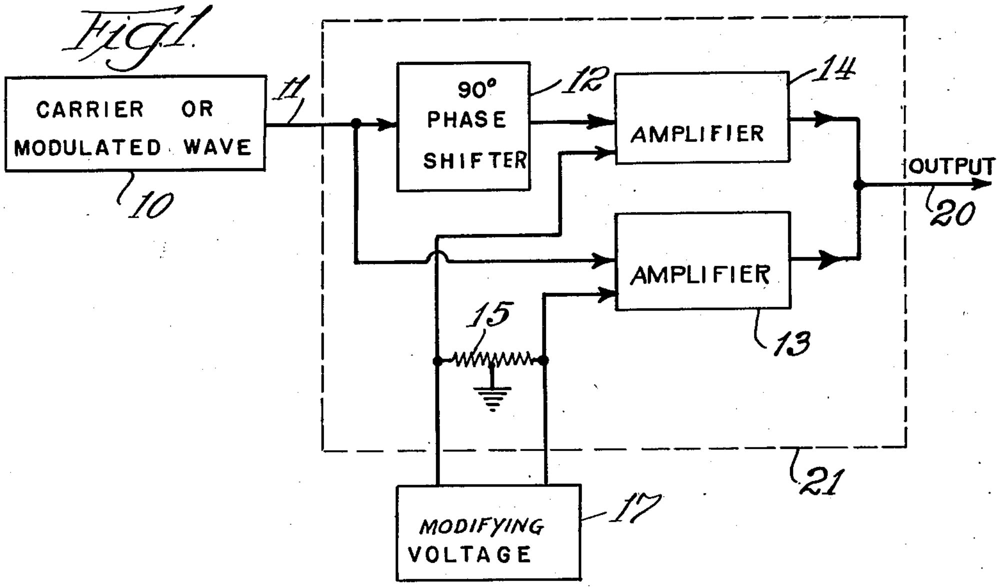

Fig. 2

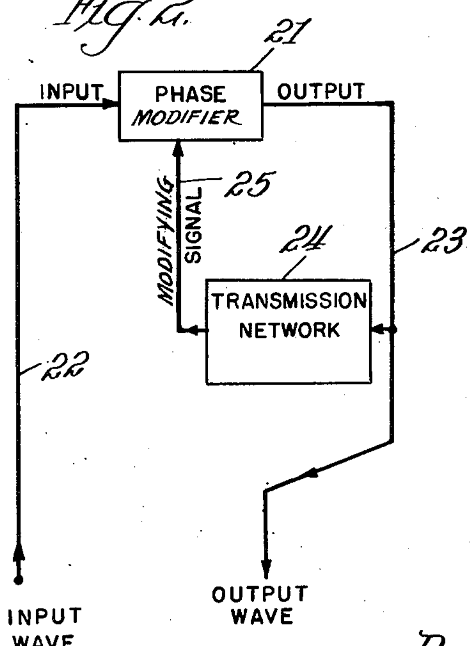

Fig. 3

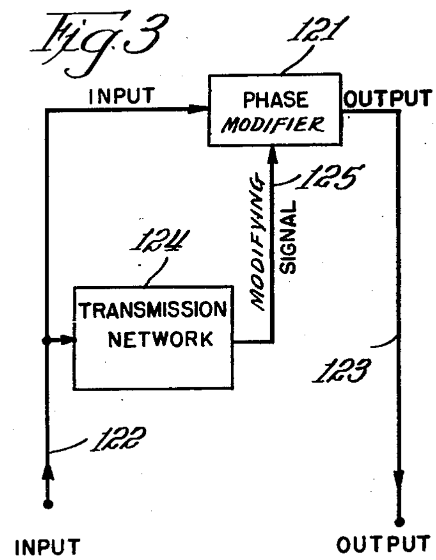

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Fig. 4.

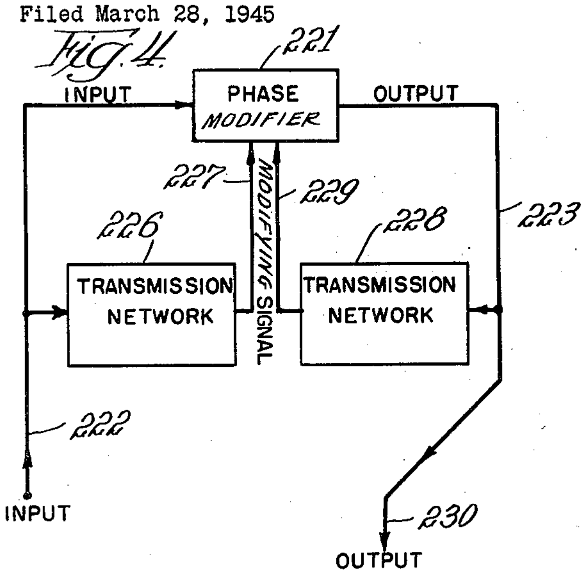

Fig. 6.

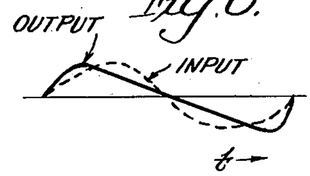

Fig. 7.

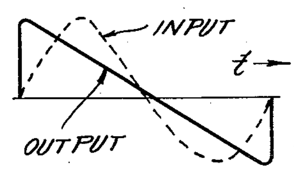

Fig. 5.

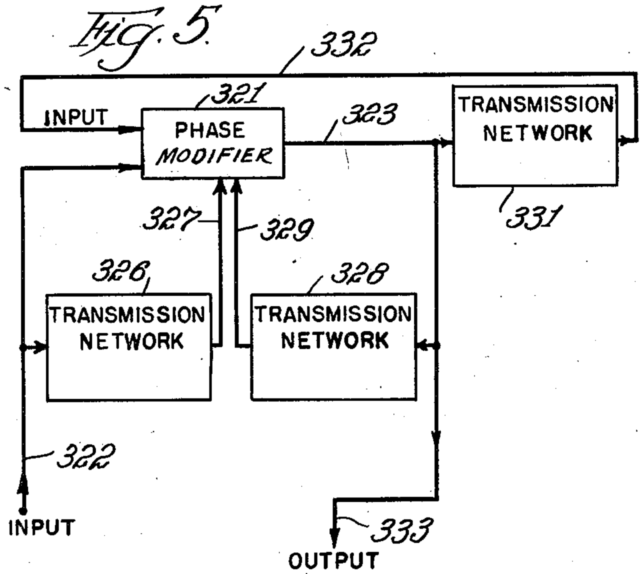

Fig. 8.

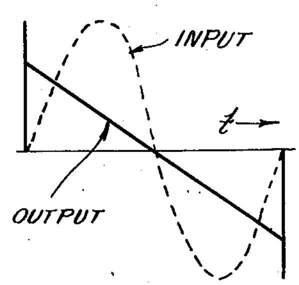

Fig. 9.

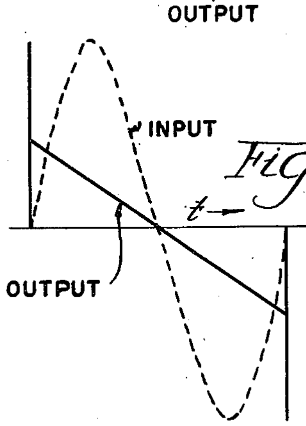

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Fig. 10.

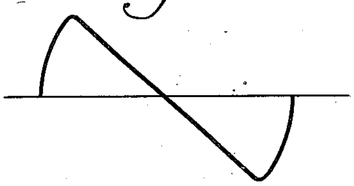


Fig. 11

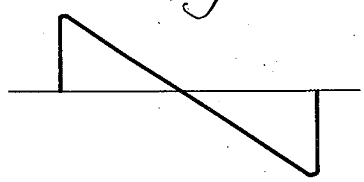


Fig. 12.

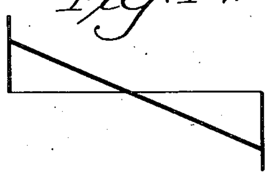


Fig. 13.

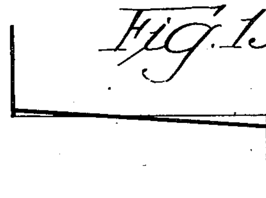


Fig. 14.

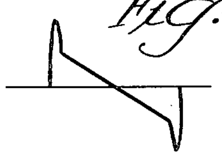
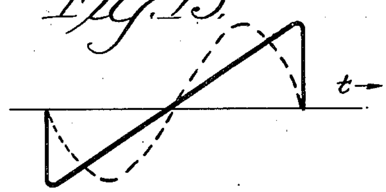


Fig. 15.



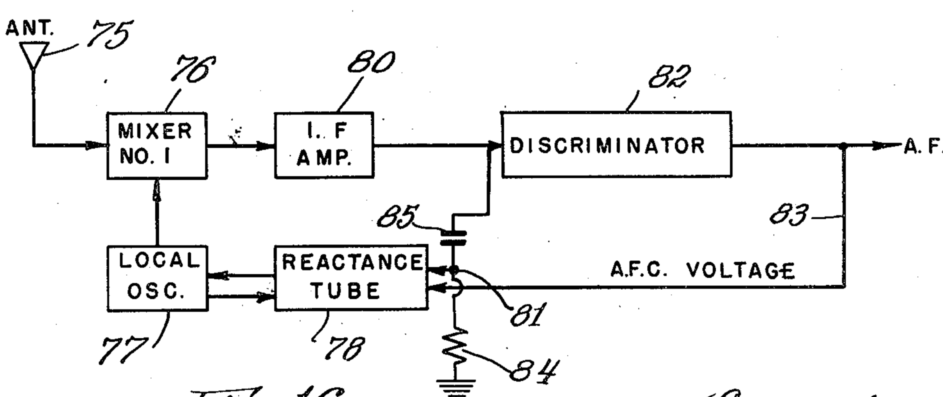


Fig. 16.

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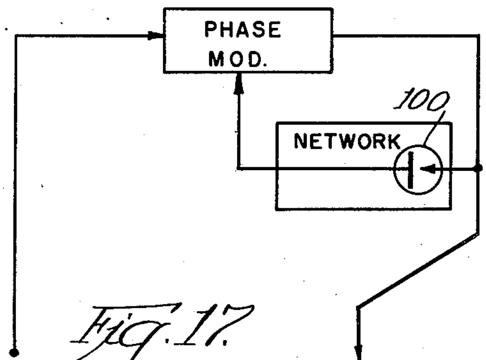


Fig. 17.

Fig. 18.

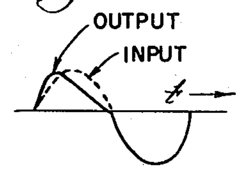


Fig. 19.

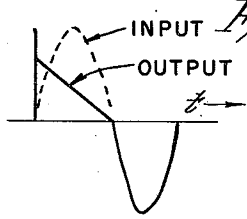


Fig. 20.

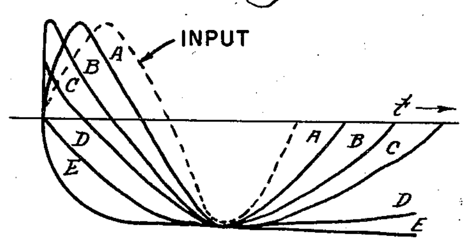


Fig. 21.

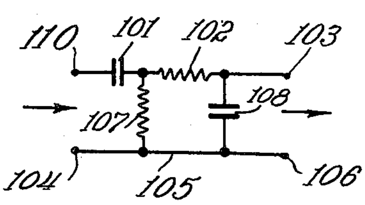


Fig. 22.

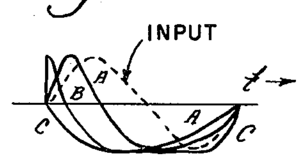


Fig. 23.

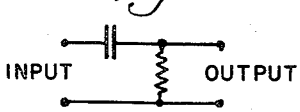
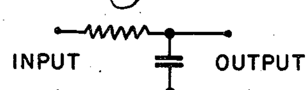


Fig. 24



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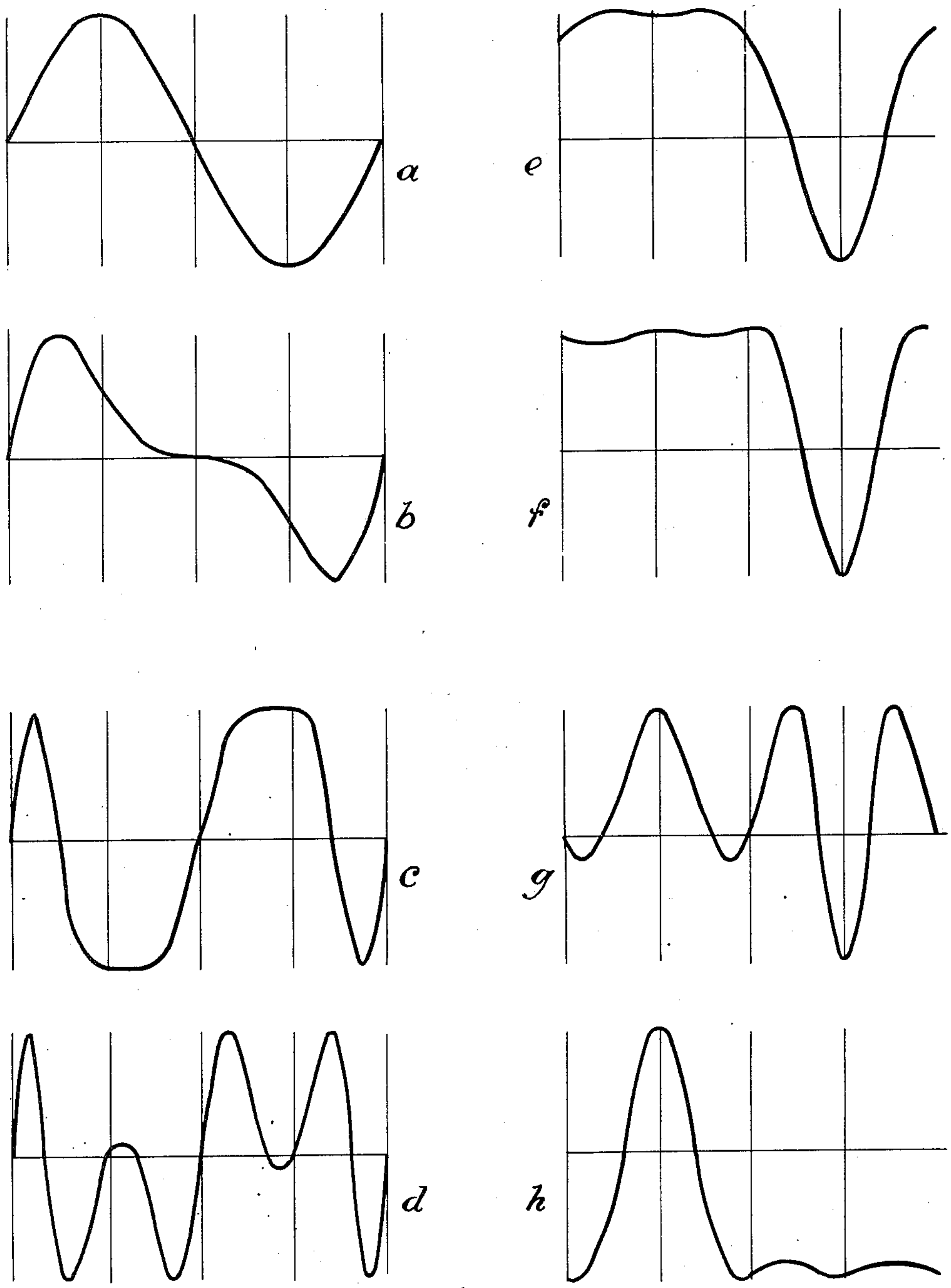

Fig 25

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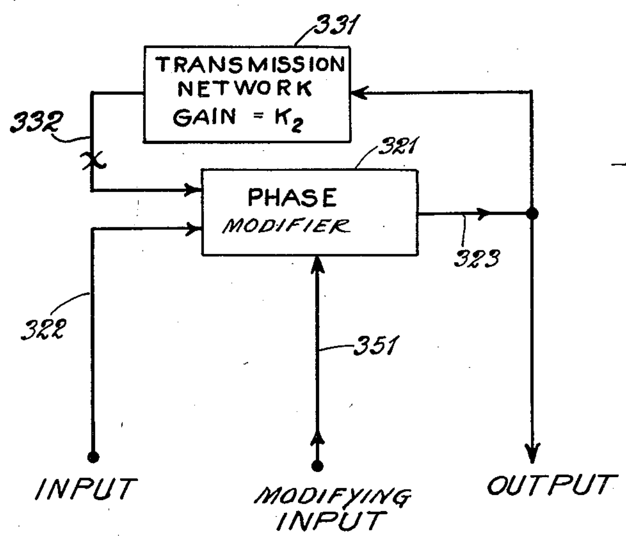

Fig. 26

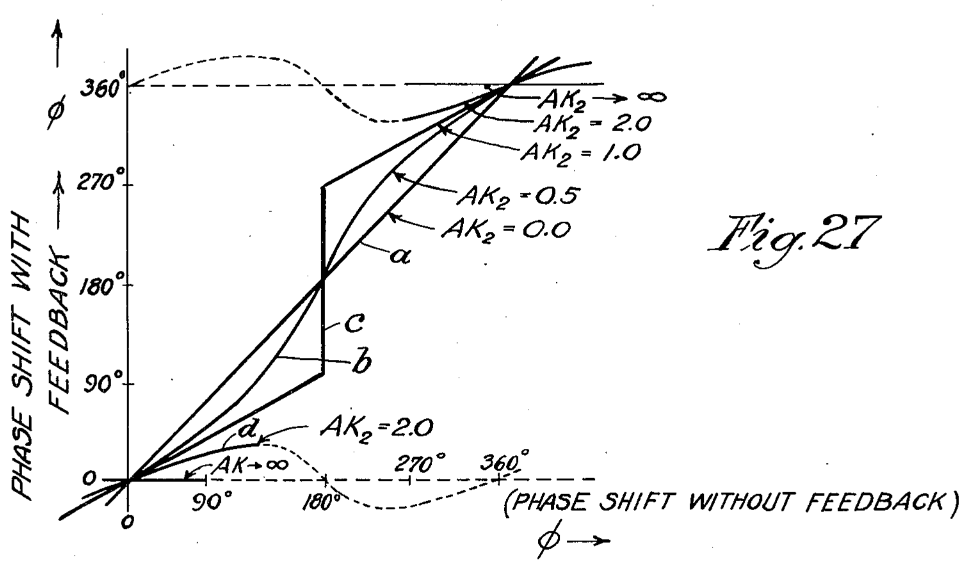

Fig. 27

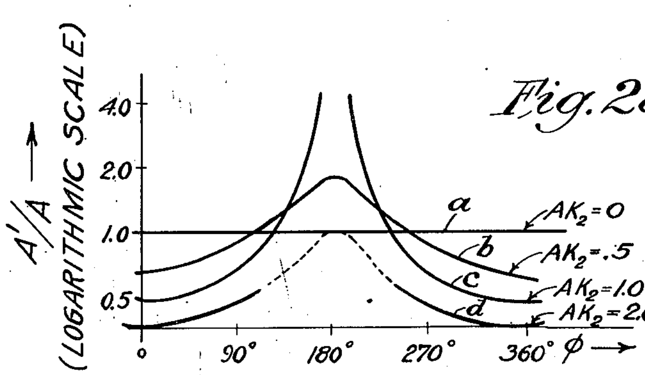

Fig. 28

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Fig. 29

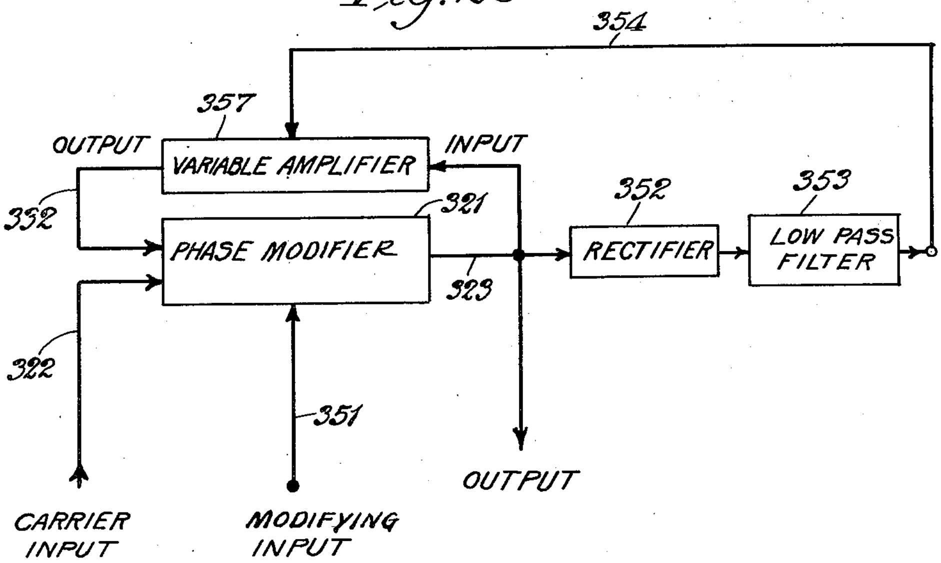
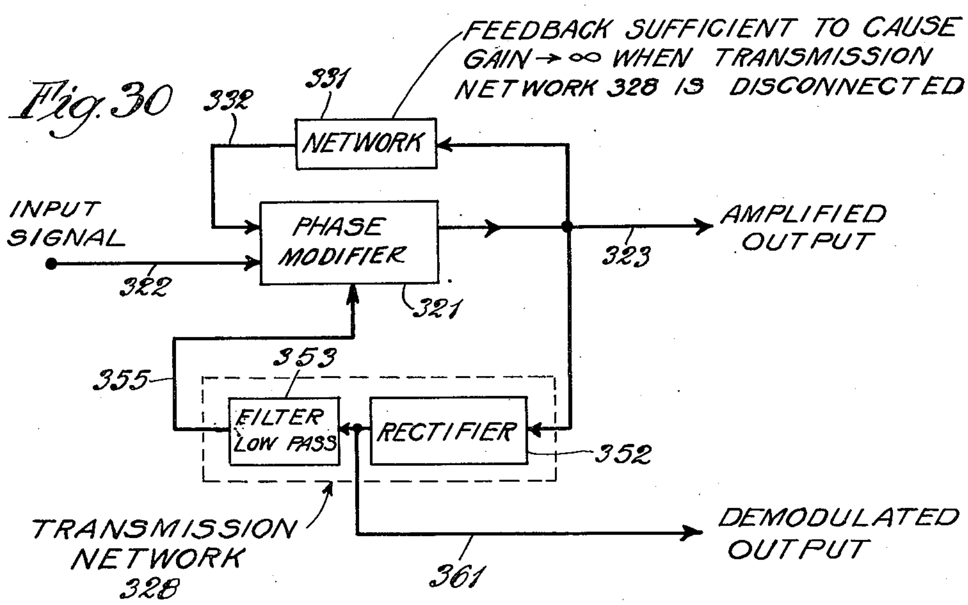


Fig. 30



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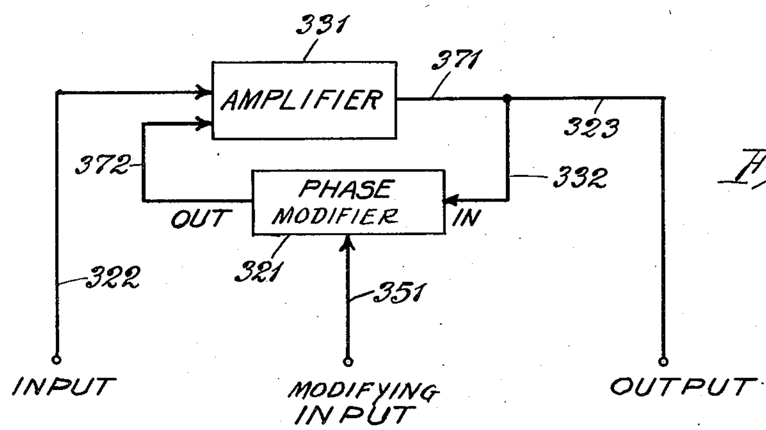

Fig. 31

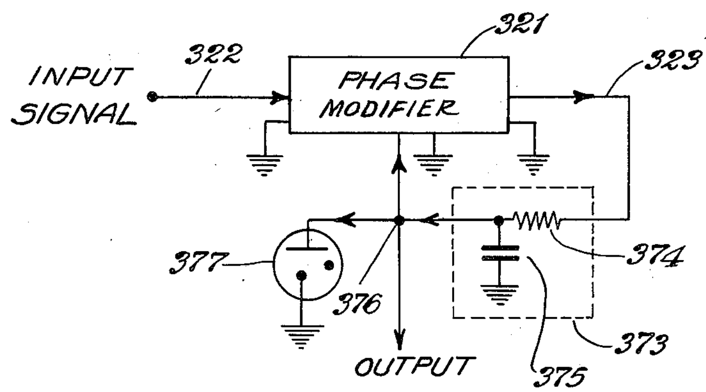

Fig. 32

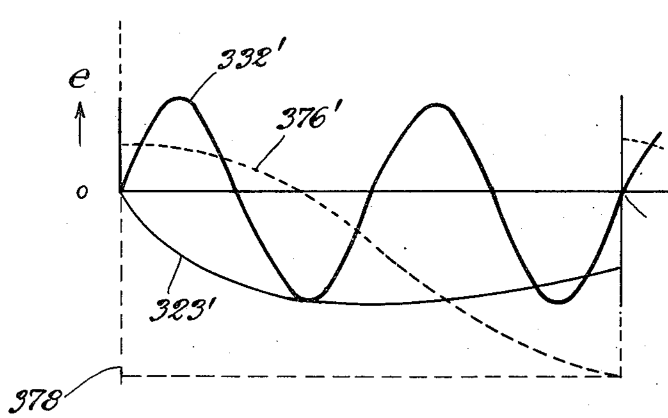

Fig. 33

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Patented May 1, 1951

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UNITED STATES PATENT OFFICE

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ELECTRICAL APPARATUS

David E. Sunstein, Elkins Park, Pa., assignor to Philco Corporation, Philadelphia, Pa., a corporation of Pennsylvania

Application March 28, 1945, Serial No. 585,257

4 Claims. (Cl. 178—44)

1

This invention relates to an electrical apparatus and particularly to a wave distorting and amplifying means. In certain types of apparatus, such as for example in television work, it is desirable to obtain sharp trigger pulses or various wave shapes from a sine wave. While it has been possible to operate on sine waves and obtain a large number of different pulses and wave shapes, the means used has been elaborate and, in general, will work only with waves of a certain frequency. It is desirable to provide a relatively simple means for changing a wave into sharp pulses or non-sinusoidal waves with a minimum of apparatus.

The invention herein accomplishes the above by utilizing a phase modifier. In general, the invention provides means for feeding a wave, such as sine wave for example, into a phase modifier and feeding back at least a part of said phase modified output to the input of the phase modifier or modifying the input wave to the phase modifier by feeding either the original wave into the phase modifier as a modifying wave, or by using the output of the phase modifier as a modifying wave or by a combination of these methods. The output of the system may be taken from a number of points in accordance with the effects desired. The character of the output is determined in a measure by the place from which the output is taken, by the amount of feedback, by the characteristics of the feedback circuits, by the input wave shape and by other related features.

One object of my invention is to provide a method and means for changing the wave shape of an electrical signal, and to thus change the harmonic content or frequency components of a wave, for any of the various purposes for which such a device is useful.

Another object of my invention is to provide a method and means for altering the period of a wave, which alteration is particularly useful, for example, when the wave is used in oscilloscopic observation of other waves under study.

A further object of my invention is to provide a reliable structure which, when operated according to the methods of my invention, produces sawtooth waves of good linearity and of easily adjustable but stable period.

Still a further object of my invention is to provide a method and means for limiting a signal in a novel manner, to produce an output signal of controllable amplitude, of the same frequency as the input signal, or of a selected different frequency.

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Further objects of my invention are to provide:

1. A novel tone generator.
2. A novel harmonic generator favoring certain predetermined harmonics.
3. A novel phase modifier of great sensitivity with stability.
4. A novel amplitude modifier of great sensitivity with stability.
5. A novel amplitude modifier of great sensitivity with stability and with high power output.
6. A novel amplifier for alternating current signals of great sensitivity.
7. A novel amplifier for amplitude modified signals with the feature of relatively constant output, irrespective of the input thereto.
8. A novel amplifier of variable selectivity.
9. A novel stable detector of great sensitivity.
10. A novel count-down circuit for counting or for frequency division.

Other objects of my invention will be evident from the description of its principles and manner of use, and of certain typical devices embodying it, as set forth in the following description and drawings.

Referring to the drawing, Figure 1 is a block diagram of a phase modifying system. Figures 2 to 5, inclusive, are block diagrams showing various forms which the invention may take. Figures 6 to 15, inclusive, are curves illustrating the operation of my system under various conditions. Figure 16 is a block diagram of a frequency modulated receiving system utilizing this invention. Figure 17 is a diagram of a system, similar to that of Figure 2 but modified by the inclusion of a rectifier. Figures 18 and 19 are curves illustrating the operation of the system of Figure 17. Figure 20 is a family of curves illustrating the operation of the device of Figure 2 wherein a particular type of network is used. Figure 21 is a circuit diagram of a band pass network which may be used in connection with the systems of Figures 2 to 5, inclusive. Figure 22 shows some curves illustrating the action of a system such as is shown in Figure 2 utilizing the network shown in Figure 21. Figures 23 and 24 show circuits that may be used as networks. Figure 25 shows a series of curves resulting from the operation of devices of my invention. Figure 26 shows a simplified version of the device of Figure 5. Figure 27 shows the phase shift produced by the device of Figure 26 under various conditions of adjustment, while Figure 28 shows the corresponding gain curves. Figure 29 shows a modified version of the device of Figure 26. Figure 30 shows a variation of the device of Figure 29, and Figure 31 is a modification applicable to the various forms of my invention, while Figure 32 represents a count-down circuit using the principles of my invention, as explained in connection with the curves of Figure 33.

In Figure 1, I have illustrated a phase modifying system, which may be used in the systems hereinafter described. Thus block **10** may provide a carrier or modulated wave or any basic wave of any shape and may, in a simple instance, be a generator of sine waves. The frequency may be any desired value. The output of generator **10** is fed to line **11** going to ninety-degree phase shifting means **12**. Phase-shifting means are well known, and a simple form of phase shifter useful with this invention may comprise either a delay line or impedance network so proportioned as to obtain the required phase shift. Phase shifter **12** supplies a signal to amplifier **14**, which amplifies the signal to an extent which is controlled by the modifying input thereto.

Line **11** also supplies signal from source **10** to amplifier **13**. Amplifier **13**, like amplifier **14**, produces an output which is its input signal multiplied by a factor which depends on the instantaneous value of the signal at its input terminals.

Modifying signals of equal value and opposite polarity may be supplied to the amplifiers **13** and **14** from a source of modifying voltage **17** through a resistance **15** having its center grounded. It is understood that all components have suitable grounds for completing circuits. Other feeding means may be used if desired. The outputs of amplifiers **13** and **14** are supplied to a common output terminal **20**. If one phase modifier does not provide sufficient phase shift in a given application, others can be added in cascade to multiply the phase shift by the number of modifiers in cascade.

The portion in the dotted rectangle **21** may be considered as the phase modifying part and may be used in the circuit diagrams hereinafter referred to.

Other forms of phase modifiers may be used, however, examples of which are shown in Figure 8 of Patent 2,240,428, issued to Travis on April 29, 1941, and in applicant's application Serial No. 554,962 filed September 20, 1944, now Patent No. 2,456,466, issued December 14, 1948. In practice, any device may be used herein as a phase modifier which provides means for producing an output wave from an input wave in such a manner that the output wave is a time-delayed version of the input wave with the amount of time delay controlled by a modifying signal. Thus a frequency modulator is applicable.

Referring now to Figure 2, phase modifier **21** may have one input **22** supplied by a suitable wave, such as a sine wave. The output of modifier **21** is fed to line **23** and supplied to network **24**. This network **24** may be either linear or non-linear. Thus, if network **24** is linear, it may consist of resistances, condensers, inductances, or amplifiers, or any combination thereof arranged to have any desired frequency characteristics. If network **24** is non-linear, it may consist of amplifiers, asymmetrical conducting devices, or other non-linear devices. Network **24** may consist of any combination of linear, and non-linear, active, and passive elements. Network **24** is connected back to phase modifier **21** through line **25**.

The output of the entire system may be taken as illustrated in the drawing or, if desired, the output may be taken from line **25**.

Referring to Figure 3, network **124** is connected between modifying input line **125** and source **122**. The output may be taken from line **123**. The operation and the possibilities of the system shown in Figure 3 are hereinafter described in greater detail.

In Figure 4, phase modifier **221** has its input **222** fed by a generator at **222** and its output is delivered at line **223**. Network **226** is connected between line **222** and input line **227** of phase modifier **221**. Another network **228** may be connected between output line **223** and a second input line **229** of phase modifier **221**. Because of these connections the input signal on line **222** is phase modified by the sum of the signals on lines **227** and **229**. The output of the system at **230** may be taken as shown.

In Figure 5, phase modifier **321** has input **322** and a network **326** connected between this input **322** and input **327** of the phase modifier . An output line **323** from the phase modulator feeds a second network **328** which, in turn, supplies a signal to line **329** going to another input terminal of phase modifier **321**. Output **323** may also feed a third network **331** whose output **332** may also be fed back into phase modifier **321**. Thus, the sum of the signals on lines **322** and **332** becomes phase modified by the sum of the signals on lines **327** and **329**. The output of the entire system at **333** may be taken as shown in the drawing although it may be taken from either side of either of the networks **328** or **331**. The effects of networks **326** and **328** will be evident from a consideration of the similar effects in the device of Figure 4. The effect of network **331** is to degenerate or regenerate the phase modifier, selectively at different frquencies, if desired. The expression "sum of signals" is intended to refer to the effective result whether the signals are vectorially added or multiplied. Thus simple addition circuits are well known. Multiplication effects are obtained by impressing signals on grids of one tube. In the latter case, the resulting frequency components are different.

It is apparent that Fig. 5 constitutes a general form that the invention may take, and that in specific embodiments it is possible to omit from Fig. 5 any one or any two of the networks **326**, **328**, and **331**. Thus Fig. 2, Fig. 3, and Fig. 4 show special modifications of Fig. 5. Other modifications are possible in which network **326** is omitted or in which network **328** is omitted or in which both networks **326** and **328** are omitted, or in which input signals are applied to network **331** or to network **328** or both instead of or in addition to the signal supplied on line **322**. Examples of some of these combinations will subsequently be described in connection with Fig. 26, Fig. 29 and Fig. 30, with a variation shown in Fig. 31.

Inasmuch as the phase displacement in the output of a typical phase modifier, such as phase modulator **21** in Figure 2, is proportional to the amplitude of the modifying voltage, it is clear that the character of the output of the phase modifier may be varied by controlling the amount of feedback. Thus, in Figure 6 (this is the case when the circuit of Figure 2 has a feedback network **24** which is substantially free of all amplitude, frequency and phase distortions), a sine wave input to line **22** is shown in dotted line, while the distorted wave present in output line **23** is shown in full line. In Figures 7, 8, and 9, the dotted sine wave input has been increased in amplitude, while maintaining the proportion of feedback constant, with the result that the output of the system has become more distorted. Thus, in Figure 7, the output is like a figure Z on its side, while in Figures 8 and 9 substantially the same shape is presevred but the vertical voltage pips are much greater.

The result of the operation of the device of Fig. 2 may be computed readily. A convenient factor θ, usually of fixed value, may be chosen, to represent the number of radians of phase shift of the output of the prase modifier (compared to the input) per volt applied to the modifying signal input terminals. An instantaneous output amplitude is selected, and the corresponding input time (phase) is determined by the phase of the incoming wave at the time it has the selected amplitude (modified by the gain of the modifier, if significant). The input phase, so found, is added to the phase delay due to the modifying voltage, to determine the time or phase of the output wave at the instant that it has the selected amplitude. This procedure is based on the formula $e_0=AB \sin (wt+\theta Ke_0)$ which governs the operation of the device for sine wave inputs. θ was defined above, e_0 is the output of the modifier, A is the absolute value of gain of the modifier, B sin wt is the input wave, and K is the complex gain in the feedback network 24. Generally, K is a function of the frequency components appearing in the output wave, but for the case considered above, K is taken as a real number substantially independent of frequency, which is the case which obtains for a linear, distortion-free feedback network for network 24.

In cases where the change in output amplitude is substantially instantaneous, the amplitude of the output is calculated by successive approximations, from the known input a small time after the instantaneous change has occurred. From a knowledge of the range of values of the output wave before it reached the value corresponding to the input wave, the pattern of the output wave before the selected small time may be determined.

In connection with Figures 6 to 9 inclusive, it is clear that, beyond a certain minimum input amplitude shown in Figure 8, the root-mean-square value of the output is substantially independent of input amplitude. Thus, in Figure 9, the input amplitude is substantially greater than in Figure 8; nevertheless, the root-mean-square value of the output remains substantially the same.

If the feedback factor is changed, instead of the input voltage, the resulting output in the circuit of Figure 2 is shown as in Figures 10 to 13 inclusive. Again linear operation of network 24 is assumed. In Figure 10, a small amount of feedback to the phase modifier is provided. It will be noted that the voltage rises are more or less curvilinear while the drops are substantially rectilinear. As the feedback factor is increased, as shown in Figure 11, the voltage rises become more linear, while the voltage drops retain their rectilinear characteristic with the slope of the drop decreasing somewhat. A further increase in the feedback factor, as shown in Figure 12, results in sharp voltage rises with pips at the two ends of the wave. In Figure 13, a still further increase in the feedback factor results in a flattening of the rectilinear portion of the voltage drop with the two pips at the ends remaining substantially as in Figure 12. In practice, the voltage pips at the ends of the wave, as shown in Figures 8, 9, 12 and 13, would not have superimposed rises and falls. Due to the time constant of the various capacitances, some time would exist between the charging and discharging due to voltage rise and drop and, as shown in Figure 14, the voltage rise is displaced along the time axis from the voltage drop by a small time interval.

From the shape of the curves of Figures 7 to 14 inclusive, it is clear that the voltage pips produced by the system have a fixed phase relation to the original sine wave input. Thus it follows that the voltage pips may be used as markers or as timing impulses. The use of such pips would usually require the elimination of the remaining portion of the wave as by passage of the waves through a bias-delayed rectifier or through a high pass filter, such as a differentiating circuit. On the other hand, if the pips are eliminated such as by conventional peak clippers or passage of the wave through a low-pass filter, then a saw-tooth wave is provided. Such saw-tooths may be employed for timing a cathode ray tube or for any other purpose.

It is possible to reverse the phase of the voltage feedback in the system shown in Figure 2, as by reversing the terminals of the input or output of the feedback network 24. Then the output will be as shown in Figure 15. In this figure, the magnitude of the input is substantially equal to that of the input as was shown in Figure 7; it being understood, however, that Figure 15 shows the dotted input wave and corresponding output wave at a different portion of the cycle than Figure 7.

Referring now to Figure 16, a limiting system utilizing the present invention is shown. This limiting system is shown as the radio frequency portion of a frequency modulated signal receiver. Thus antenna 75 may feed energy of any desired type to mixer 76. The mixer 76 in its most simple form may consist of a two or three element detector. Mixer 76 is also fed by local oscillator 77 of any desired type. Inasmuch as the combination of a local oscillator and mixer is well known in superheterodyne circuits, a detailed showing and description is unnecessary. Local oscillator 77 is coupled to reactance tube system 78 so that the frequency of oscillator 77 may be varied by the reactance tube. A system of this character for controlling the frequency of an oscillator is well known and is described for example on pages 2152 and 2153 of Standard Handbook for Electrical Engineers (7th edition).

The output of mixer 76 may be fed to intermediate frequency amplifier 80, it being understood that the band width of amplifier 80 will have to be wide enough to accommodate the various frequencies required.

Reactance tube 78 is controlled by the output of amplifier 80. The output of amplifier 80 may be fed to discriminator 82 of any desired type, such as is shown for example on page 655 of Radio Engineer's Handbook by Terman (1943 edition). The output of discriminator 82 will supply an audio frequency which may be fed to suitable amplifiers for use in a loud speaker. The output may also contain voltages for controlling the local oscillator frequency and, to this end, line 83 may be fed from the output of discriminator 82 to reactance tube 78. Thus, as shown on page 655 of Terman's book, particularly Figure "c", the output of the discriminator may be fed back to one of the control electrodes of the reactance tube so that the reactance tube may function to maintain any given received signal centrally tuned with respect to the frequency band passed by the intermediate frequency amplifier.

It is preferable that feed line 81 into reactance tube 78 should include a differentiating circuit in order to change the frequency modulator, made up of local oscillator 77 and reactance tube 78, into a phase modulator. Thus, an appropriate differentiating circuit may consist of a resistance 84 and series capacitor 85. The effective value of resistance 84 so far as differentiating action is concerned is made up in part of a discrete resistance and in part by the internal resistance of the output circuit of the mixer 76 or amplifier 80. It is apparent, then, that the limiting system of Fig. 16 functions in a manner similar to that described in connection with Fig. 2 and by the curves of Figs. 6 to 9 inclusive to prevent amplitude modulation from appearing at the input of discriminator 82.

It is possible to provide for asymmetric action by inserting a half wave rectifier in the feedback path of a system utilizing the invention herein. Thus Figure 17 is substantially the same as Figure 2 with the exception that the specific case is considered in which rectifier 100 is disposed in the feedback path. It is clear that, when the rectifier does not conduct, the phase modifier will merely function as an ordinary amplifier so that one-half cycle of the output will be a sine curve, when the input wave is sinusoidal. Since the rectifier conducts on the other half cycle, the output wave will resemble that of Figures 6 to 15 inclusive on said half of the cycle. This is shown in Figures 18 and 19. In Figure 19, the input voltage is greater than in Figure 18.

In the system shown in Figure 2 having characteristics as shown in Figure 6 to 19 inclusive, it was pointed out that the network used to feed the output of the phase modifier into the input thereof has been capable of passing substantially all the frequency components appearing in the output of the phase modifier.

However, it is possible to have the network constants adjusted to different values so that the network causes frequency discrimination. Thus, if a network of resistances and condensers such as shown in Figure 23 has a time constant small in comparison to the period of a cycle, then a differentiating action will result. On the other hand, if the circuit of Figure 24 is used and if the time constant is large in comparison to the period, then an integrating action will result. Thus in Figure 20, there is a family of curves corresponding to the curves shown in Figures 10 to 13 inclusive wherein Figure 2 has an integrating transmission network like that of Fig. 24 and wherein the input to Fig. 2 is sinusoidal. It is apparent that the same set of curves would obtain if the integrating network is omitted and the phase modifier is altered to the extent that it becomes primarily a frequency modifier, as previously indicated. Referring to Fig. 20, curve A shows the output with a small amount of signal fed back. As the amount of signal fed back is increased, the curves take on the forms shown successively in B to E inclusive. It is apparent that in E, the curve is no longer periodic. The ultimate result will be that the system will become overloaded, but until that occurs the response will follow these curves shown. When incorporating the circuit of Figure 24 into the feedback network of Figure 2, it is preferred to have means for periodically discharging the integrating circuit so that the system of Figure 2 will not overload as time goes by. This overload results from the fact that output frequency is not equal to the input frequency, and as pointed

out in connection with Fig. 32 it may be put to a useful purpose.

It is possible to provide a network in the feedback circuit which network will have non-uniform action on various frequencies. Thus, it is possible to provide a network having a band-pass characteristic, and a simple network of this character is shown in Figure 21. In this figure, terminal 110 may be connected through a condenser 101 to resistance 102 and thence to one output terminal 103. The other input terminal 103 may be connected by line 105 to the other output terminal 106. A resistance 107 and condenser 108 are connected on opposite sides of resistance 102 to line 105.

In Figure 22, some curves are given showing the output of a system, such as shown for example in Figure 2, wherein the network is of the band-pass type. The dotted line sine curve is the input while curves A, B, and C give the output for various values of feedback. As the feedback increases, the output takes on successively the shape of curves A, B, and C. In this particular case, the frequency applied to the input of Figure 2 was above the pass band, so that the network tended to integrate, yet series condenser 101 causes the period of the output of Figure 2 to be equal to the input period. The same set of curves is obtained if a frequency modulator is used as modifier 21 in Fig. 2, and if, at the same time, resistor 102 and capacitor 108 are omitted from the feedback network shown in Fig. 21 as used as network 24 in Figure 2.

Thus far, the action of the invention has been described primarily with reference to Fig. 2. Referring now to Fig. 3, the output of the phase modifier is given for sinusoidal inputs by:

$$e_0 = AB \sin (wt + K_1\theta B \sin wt)$$

where e_0 is the output wave, B sin wt is the input to Fig. 3, A is the gain of the phase modifier, K_1 is the complex gain of network 124 (which in general is a function of frequency), and θ is the phase sensitivity of the phase modifier, which may be defined as the amount of phase shift introduced by the phase modifier per unit volt applied as a modifying signal thereto.

It can therefore be demonstrated that if the transmission network 124 is a linear device producing no appreciable phase shift or amplitude distortion, the output wave e_0 has, for sinusoidal input signals, the form given by Figure 25. If, as in Fig. 25*a*, the network 124 has zero gain the output wave is sinusoidal. In Fig. 25*b* the output wave is seen to be considerably distorted with respect to the input wave, given by Fig. 25*a*. Fig. 25*b* applies to the case of the network 124 having a gain such the product of this gain (K_1) by the phase sensitivity of the modifier (θ) by the peak value (B) of the input signal is approximately 57.3°, or one radian. Further increase of either K_1 or θ, results in the curve of Fig. 25*c*. It will be noted that considerable second harmonic is present, whereas in Fig. 25*b*, predominantly third harmonic is present. Still further increase of either the gain of network 124 or of the phase sensitivity of the modifier causes the output wave to take the form shown in Fig. 25*d*. Fig. 25*d* shows that considerable fourth harmonic is present as well as some fundamental. A further increase of the product of K_1 by θ causes successively higher harmonics to be produced, with relative attenuation of lower order harmonics.

Thus the device of Fig. 3 comprises a useful harmonic generator or frequency multiplier. It can be seen that one particular relatively pure harmonic wave may be produced with an amplitude substantially greater than the other components of the wave. It will be noted that in the production of this second harmonic, no zero component, or D. C., is produced.

It will be apparent from consideration of the equation given above in reference to Fig. 3 that increase of the amplitude (B) of the input wave has an effect generally similar to an increase of either the gain (K_1) of network 124 or of the phase sensitivity (θ) of the modifier. Thus, with particular values of input amplitude, of gain of the network 124, and of phase sensitivity, the solid curve of Fig. 25*b* appears in the output. If now, holding other conditions of the system constant, the input amplitude is increased, then the output wave will successively take the general shapes of Figs. 25*c* and 25*d* for successively greater values of input amplitude. However, in this case, the output wave will of course have an amplitude proportional to the amplitude of the input wave, whereas the figures which represent increasing amounts of gain of network 124 or of phase sensitivity, indicate a constant output amplitude. Therefore the actual output wave amplitude is, in this case of increased input, a multiple of the values of curves of Figs. 25*c* and 25*d*.

In further illustrating the operation of Fig. 3, a network may be considered for an adjustment of network 124 which causes a 90° phase shift of the signal passing therethrough, network 124 having an adjustable gain. Then for the case of sine wave input the output wave becomes as shown in Figs. 25*e*, 25*f*, and 25*g*, which represent successively increasing values of the magnitude of $B\theta K_1$. Figs. 25*e* and 25*g* represent values of the magnitude of $B\theta K_1$ corresponding to those in Figs. 25*b* and 25*c* respectively. It will be noted that the phase shift introduced by network 124 markedly alters the output wave shape, and to a certain extent also the frequency components thereof. Generally speaking, if network 124 has a phase shift other than 0° or a multiple of 180°, there will be a D. C. component in the output wave, and there will also be dissymmetry of the output with respect to the 180° points of the input wave. However, increase of the magnitude of the product $B\theta K_1$ has the same general effect irrespective of the phase of K_1; that is, such an increase causes inclusion in the output of successively greater amounts of higher order harmonics.

It will be noted that the curves in Figs. 25*e*, 25*f* and 25*g* may also be obtained by employing a network for network 124 which has substantially zero phase shift and simultaneously employing, as the phase modifier 121, a modulator which produces a frequency dependent upon the instantaneous value of the modulating signal.

In Fig. 3, the phase of the modifying signal may be changed 180° by reversal of the leads to network 124 or to the modifier from said network. Such reversal does not change the frequency components of the output wave, but does change the phase of said components; so that the resultant output may appear as in Fig. 25*h*. Fig. 25*h* represents conditions substantially the same as Fig. 25*f*, except that the above polarity reversal has been effected. It can be seen that the output wave has likewise suffered the equivalent of a polarity reversal, plus also a shift in time.

It is apparent from Figs. 25*a* to 25*h* that Fig. 3 provides a means of altering an input wave in a wide variety of desirable manners. Applications of the device include uses as a novel frequency multiplier and as a novel tone generator. As a frequency multiplier, the device can be made to have an output containing a relatively pure sine wave signal at a multiple of the input frequency, and the multiple, so produced, can be varied by variation of either the input signal, the gain of network 124, or the sensitivity of the phase modifier. Though the output may be a relatively pure sine wave signal, any further degree of purity may be obtained by employing suitable filters in the output circuit. By a different adjustment of the value of $B\theta K_1$, it is possible to produce an output containing several adjacent high order harmonics of the input signal, with relatively great strength compared to the fundamental and lower order harmonics. Thus, the apparatus of Fig. 3 provides a useful adjunct to a frequency standard used to generate harmonics of the signal supplied thereto, for any of the purposes for which such frequency standards may be employed. As an additional application of the method of Fig. 3, it will be noted that such a device constitutes a novel tone generator for electronic musical instruments. By changing the input thereto, or by changing the attenuation or phase shift of network 124, by any well known method, a tone may be produced which can effectively be continuously varied in timbre and pitch, yet still the fundamental of tone produced is harmonically related to the incoming wave. The timbre of any given note may be gradually altered so as to favor higher harmonics and remove the lower ones.

Referring now to Fig. 26, there will be seen the previously mentioned special case of Fig. 5 in which networks 326 and 328 have been omitted. All components in Fig. 26 having similar functions to corresponding components in Fig. 5 have been correspondingly numbered. Thus the output on line 323 of Fig. 26 is the phase modified signal produced by modifying the sum of the input signal on line 322 and the feedback signal on line 332, by the signal supplied from the modifying input signal on line 351. It can be shown that the output on line 323 is given by the following equation for the case of sinusoidal input signals:

$$e_0=\frac{AB\sin\left[wt+\phi-\tan^{-1}\frac{AK_2\sin\phi}{1+AK_2\cos\phi}\right]}{\sqrt{1+(AK_2)^2+2AK_2\cos\phi}}$$

in which B sin wt is the input signal, A is the gain of the phase modifier, ϕ is the phase shift therethrough, and K_2 is the gain of the feedback network 331. ϕ is of course under control of the modifying input supplied on line 351. For the purposes of this analysis, it may be assumed that no phase shift is experienced in the feedback network 331, though if there were phase shift encountered in said path, then it may be taken into account by including any such shift as part of the value of ϕ, and also entering such shift with a negative sign as an additional term of the polynomial in the brackets of the above equation. From the above equation, the curves of Fig. 27 and Fig. 28 may be plotted to enable a better understanding of the operation of the system shown in Fig. 26.

Thus in Fig. 27 is shown the actual phase shift

ϕ' between the output and input signals of Fig. 26 plotted against the phase shift ϕ introduced by the phase modifier between the output thereof and the net input thereto, for various values of the product AK_2, which product is the magnitude of the gain around the feedback path in Fig. 26 in the absence of a feedback connection to the circuit. This gain may be measured or computed by opencircuiting the feedback path at some point, such as point X on line **332**, and then applying a signal to one end of the line so broken and measuring the magnitude of the signal formed at the other end of the line so broken, the gain being the ratio of the magnitude of the latter signal to that of the former. Curve *a* in Fig. 27 represents operation with the above defined gain being zero; and as would be expected, the phase shift produced is a straight line of unity slope, the phase shift being due solely to the action of the phase modifier, which is operating without feedback. As the factor AK_2 is increased from zero to unity, the operational characteristic takes successively the forms shown by curves *a*, *b*, and *c*. Thus curve *b* represents a value of $AK_2=0.5$. It can be seen from curve *b* that for a phase shift, ϕ, introduced by the phase modifier, of 0° to 180°, the net phase shift, ϕ' introduced by the system of Fig. 26 is less than the phase shift ϕ introduced by the phase modifier; and that for phase shifts introduced by the phase modifier of 180° to 360°, the net phase shift is greater than that due solely to the action of the phase modifier. Moreover, the slope of curve *b* is less than that of curve *a* for values of ϕ between approximately $-90°$ to $+90°$. In this region of operation, therefore, it is apparent that the total phase shift ϕ' introduced for a given modifying signal is less than that which would have been introduced by the same modifying signal in the absence of feedback. Thus, if operation is restricted to this portion of the characteristic, a degeneration of phase shift has been accomplished, with a consequent reduction of phase sensitivity of the system of Fig. 26. However, over the portion of the curve between $\phi=90°$ to $\phi=270°$, approximately, the slope is greater than unity. Consequently, if operation is employed over this portion of the curve, the phase sensitivity of the modifying system is increased by the feedback action. Such operation may be obtained by properly connecting the feedback terminals of network **331** so that the feedback is regenerative rather than degenerative in the absence of a modifying input signal to line **351**.

Therefore, it is apparent that the system of Fig. 26 may be used to increase the effective sensitivity of any given phase modifier or modulator or frequency modulator, particularly when the maximum desired phase deviation due to modifying or modulation is less than ±90°. Thus the method will permit economizing in the apparatus used to supply signal to modifier or modulate the phase modifier or modulator by virtue of permitting a reduction of the power requirements thereof.

A still further increase of the value AK_2, as shown by the curve *c* of Fig. 27, which represents a value of $AK_2=1.0$, further augments the effects described above in connection with curve *b*. Thus, in curve *c* there is a substantial reduction of phase sensitivity for values of ϕ' between $-90°$ to $+90°$, but there is a very great increase (theoretically infinite) in the phase sensitivity of the system for values of ϕ' between 90° to 270°. In this manner, therefore, the phase sensitivity of the modifier or modulator may be increased to any desired value, merely by making the value of AK_2 as close as desired to unity. This can be done by adjusting the gain either of the phase modifier or modulator **321** or of network **331** in any suitable manner. Though such adjustment could be fixed by design, or be made manually, in order to realize maximum sensitivity and at the same time have stability it is desirable that the adjustment be made automatically, as will become evident from the curves of Fig. 28; and a method of accomplishing the automatic adjustment is described in connection with Fig. 29.

In Fig. 28 there is shown the relative gain of the device of Fig. 26 plotted as a function of the phase shift ϕ due to the phase modifier or modulator, for various values of the factor AK_2. The relative gain is defined as the ratio A'/A, where A' is the gain of the system with feedback (i. e. the ratio of the magnitude of the signal appearing on line **323** of Fig. 26 to the magnitude of the signal necessary on line **322** to cause said former signal), and where A is defined, as above, as the gain of the phase modifier or modulator without feedback. In curve *a* is shown the gain characteristic when AK_2 is zero (no feedback) It can be seen that then the gain may be independent of the phase shift ϕ. However, as the feedback is successively increased, as indicated by curves *b*, *c*, and *d*, the relative gain is seen to pass through a maximum at $\phi=180°$, with the value of the maximum dependent upon the value of the factor AK_2. Thus curve *b*, which represents a value of AK_2 of 0.5, has a peak of magnitude equal to 2.0; and curve *c*, for which AK_2 is unity, has a peak of theoretically infinite amplitude, representing the fact that the system is on the verge of self-sustained oscillation when $\phi=180°$. From the curves of Fig. 28 it therefore becomes apparent that it is ordinarily preferable to incorporate limiters in the output circuit of Fig. 26 when employing the system thereof as a phase modifier or modulator operating on the steep portions of the curves of Fig. 27 or 28.

Also from Fig. 28 it becomes apparent that the system of Fig. 26 may be used as a novel amplitude modulator or mixer, by operating over the portion of the curves of Fig. 28 to either the right or left of the peaks thereof. This can be done by supplying the proper phase shift around the feedback path of Fig. 26 in the absence of a modifying or modulation signal supplied to line **351**. In this manner, the input supplied to line **322** becomes amplitude modified or modulated by the signal fed to line **351**, and the output on line **323** may then be filtered if desired to select only certain of the frequencies produced by the system.

Referring again to Fig. 27, it can be seen by curves *d* and *d'* thereof, which represent a value of AK_2 of 2.0, that when the factor AK_2 is increased beyond a value of 1.0 the phase shift characteristic becomes discontinuous, so that ordinarily operation cannot be achieved over the dotted portion of the curves without self-sustained oscillation taking place. Likewise, in Fig. 28, curve *d* is shown dotted over that region in which oscillation may be encountered. Thus it becomes evident that for operation of Fig. 26 in the capacity of an improved phase modifier or modulator, it is preferable to prevent AK_2 from exceeding a value of unity. As indicated previously, this may be done by manual adjustment or by suitable design, but in order to operate with maximum phase sensitivity such adjustment becomes rather critical. Therefore the automatic adjustment means provided by Fig. 29, to be described subsequently, may be employed.

Another variation of the method of operation of Fig. 26 which finds wide application comprises operating the system therein in the dotted region of the curves of Figs. 27 and 28. This may be accomplished by making AK_2 equal to or greater than 1.0, as by properly proportioning the gain of modulator 321 or transmission network 331, and by operating on at least a part of the input cycle supplied to line 351 with a phase shift, ϕ, between 90° to 270°. In this manner, self-excited oscillations are produced, which may be synchronized in frequency with a small input signal supplied to line 322. In this manner it is possible to permit the signal on 351 to cause the system to go in and out of oscillation, or in other words, to be switched on and off; or alternatively to be modified or modulated from one frequency or phase of oscillation to another frequency or phase of oscillation, for such purposes as generation of telegraphic frequency modulated or phase modulated signals, and the like.

Figure 29 shows a modified version of the device of Fig. 26. In Fig. 29, elements having a common function to corresponding elements of Fig. 26 have been correspondingly numbered. Thus phase modifier 321 produces an output signal on line 323 which is the sum of the signals on lines 332 and 322 shifted in phase by an amount controlled by the modifying signal supplied to line 351. The signal supplied to line 332 is obtained by passing the output signal on line 323 through the variable amplifier 357, the characteristics of which are under control of a signal supplied thereto by line 354. The variable amplifier 357 may have either variable gain, or variable phase shift, or a combination thereof. Since amplifiers with variable gain controlled by a gain controlling signal are well known in the art, more detail thereof is deemed unnecessary. An amplifier with controllable variable phase shift is in reality a phase modifier or modulator, and hence variable amplifier 357 may take the form shown in Fig. 1 previously described. A rectifier 352 supplied with signal from line 323 feeds a low pass filter 353 having a characteristic such that preferably it will pass only those frequencies which are lower than the modifying frequencies supplied on line 351 and lower than the frequency of the input supplied to line 322. The output of the filter supplies signal to line 354. The rectifier and filter combination serves to alter the gain or phase shift of amplifier 357 or both in such a manner that when the output signal on line 323 exceeds a predetermined value, indicating that the phase modifier 321 with feedback supplied through network 357 is near the point of self-oscillation, the gain or phase shift of amplifier 357 or both is altered in such a direction as to lessen the tendency toward self-oscillation. In this manner, the phase modifier is always kept operating in a very sensitive yet stable state.

It is apparent that, in Figure 29, filter 353 may directly feed its output to phase modulator 321, such direct feed being either supplemental to the feed in line 354 or instead thereof. The supplemental feed supplies an additional modifying signal to phase modifier 321, thereby altering the D. C. component of phase shift afforded therethrough in such a manner that the operating point as represented in either Fig. 27 or 28 may be shifted to the right or left an amount sufficient to prevent oscillation as soon as any tendency thereof is felt by the rectifier 352. The supplemental feed may be used without line 354, in which case the amplifier 357 may have fixed rather than variable characteristics and may be similar to the network 331 of Fig. 26. Thus Fig. 29 may constitute another special case of Fig. 5 in which network 328 is composed of rectifier 352 and filter 353 in cascade, and in which network 326 is omitted.

In Fig. 29, as in Fig. 26, when employing the apparatus thereof as a phase modulating system, it is preferable to incorporate an amplitude limiting device in the output circuit thereof in order to reduce the amplitude modulation components appearing in said circuit as a result of the phase modulation process. However, the device shown in Fig. 29 like Fig. 26, may advantageously be employed as an amplitude modulator or mixer. The automatic threshold adjustment feature of Fig. 29 provides an amplitude modulator of great sensitivity and stability.

A variation of the method of operation of Fig. 29 enables the system thereof to be used as a novel amplifier or detector of great sensitivity, as shown in Fig. 30, wherein components of the structure having characteristics and functions corresponding to like components of Fig. 29 or of Fig. 5 have been given corresponding numbers. Thus in Fig. 30, the system and operation is similar to that of Fig. 29 except that the input signal supplied through line 351 is omitted and the output of filter 353 is fed by line 355 to phase modulator 321. Examination of curves *b* and *c* of Fig. 28 reveals that when the value of AK_2 is near unity and when the value of ϕ is near 180°, then the effective gain, A′, of the system may be many times as great as the gain of the phase modifier acting without feedback. Therefore, in Fig. 30, the phase shift introduced by the phase modifier is maintained near 180° by virtue of the network 328. If, however, the gain of the system becomes excessively large, indicating a tendency toward oscillation, then the rectifier 352 will function to alter the phase shift produced by modifier 321 and thereby to reduce the gain to a point sufficiently less than the assumed value to insure stability of operation without self-excited oscillation being permitted to build up. Thus an amplified version of the input signal supplied to the input line 322 of Fig. 30 may be obtained on line 323, and if desired, in case the input signal is amplitude modulated, the modulation component thereof may be obtained as an output on line 361. It can be appreciated that the device of Fig. 30 therefore constitutes a sensitive and stable amplifier or demodulator, suitable for use as radio or intermediate frequency amplifier in radio receivers and the like. When employing the system in such applications as radio reception, it is ordinarily preferable to incorporate tuned circuits in the input or the output circuits of the phase modifier or modulator 321 or both so that a degree of frequency selection may be achieved. It will be noted that with this novel circuit the effective selectivity is ordinarily greatest for the condition of weak input signals; and with strong input signals, the selectivity is lessened somewhat. Furthermore, it will be noted that the net amplification of the system is greatest for weak signals, and lesser for strong signals. This is a condition which is frequently desirable because it tends to make the output signal strength independent of input signal strength, thereby reducing the effects of fading, and the like.

An alternative arrangement of the apparatus of Fig. 26 is shown in Fig. 31, which may be employed for any of the applications mentioned for the system of Fig. 26 or the variations thereof. In certain applications, particularly where high power output is required, the method of Fig. 31 may be superior to that of Fig. 26. In Fig. 31, the input to the system on line 322 is supplied to the input of an amplifier 331 corresponding to the network 331 of Fig. 26. Also supplied to the input of the amplifier is the output signal, line 372, of the phase modulator 321. The input to the phase modifier or modulator is supplied through line 332 by the output signal of the amplifier 331 on line 371, which also supplies the output of the system on line 323. Thus the amplifier is responsive to the sum of the signals on lines 322 and 372. The operational characteristics of Fig. 31 are similar to those shown in Figs. 27 and 28, and hence it is apparent that the method of Fig. 31 may be adapted to any of the various forms and applications above described in connection with Fig. 26. In Fig. 31, however, the output power is determined primarily by the power capabilities of the amplifier, which may be designed for high power output more readily than the phase modifier or modulator of Fig. 26, which is the limiting factor of the power output in that arrangement. Thus the system of Fig. 31 proves advantageous for application in phase, frequency, or amplitude modulated transmitters, and the like.

Referring again to the overloaded condition of the system discussed in connection with Fig. 20, and the means for periodically relieving the overloaded condition, as shown in Fig. 32, such means may be provided by employing a conventional trigger circuit responsive to the voltage across the condenser of the integrator. One such circuit comprises connecting in parallel with the condenser 375 of the integrator 373 a gaseous discharge diode 377 (or a triode), arranged to be ionized when the voltage thereacross reaches a predetermined value, so as to lower said voltage rapidly to the starting value. This action enables the voltage to be built up with ensuing cycles of the input wave fed into the phase modifier or modulator 321 at 322 so that the discharge will again occur when the voltage reaches the predetermined value. Alternatively, as previously indicated, the integrating circuit 373 may be omitted if the phase modifier or modulator 321 is in the form of a frequency modulator. In this case, the triggering circuit 377 may be connected directly across the modifying or modulating input terminals of the modulator.

It is apparent that the operation of Fig. 32, is such that a frequency count-down action may be obtained. Thus, if the output of Fig. 32 be taken from junction 376, a pulse will be obtained in the output periodically.

Figure 33 shows the potentials at the various terminals of the device of Fig. 32, plotted against time. For ready comparison they are superimposed. Curve 332′ represents the sine wave signal applied to terminal 332. Curve 323′ represents the output wave at terminal 323, as produced by the action of the phase modifier or modulator 321 under the control of the appropriate signal shown in Fig. 33 as curve 376′. It will be noted that curve 323′ corresponds to curve D of Fig. 20, as it is produced in the same manner. The control signal 376′ is produced by the action of the integrator 373 on the signal 323′ applied to the input terminals of the integrator. Voltage level 378 represents the voltage at which gas tube 377 will start to conduct, and, it is evident from the shape of curve 376′ that the cycle of action is terminated, and a new one commenced at the point where the tube 377 fires. As shown, an output cycle 376′ is produced for every two cycles of the input wave, although by adjusting the value of voltage level 378 at which tube 377 will fire, the circuit may be used to count other numbers of cycles than two.

Although the detailed shapes of curves 323′ and 376′ cannot be shown on any conventional graph, study of the action of the circuit of Fig. 32 will show that curve 323′ starts at zero, rises to maximum and falls to zero, before it starts the slowly changing negative part of its cycle. At the end of the cycle, it rises through zero to maximum, falls to negative maximum, and returns to zero, all before the new cycle starts. No attempt has been made to illustrate the details of this action graphically. Curve 376′, on the other hand, starts at zero, rises to its maximum, and during the cycle, gradually falls to its maximum negative value, a value which is shown as about three times its maximum positive value. Immediately upon the operation of the trigger tube 377, the curve 376′ rises vertically to its maximum positive value.

Thus the output period of the device of Fig. 32 will be a multiple of the input period, and the multiple desired may be selected by proper choice of the triggering potential or of any of the gain factors included in the feedback circuit. The system therefore provides a stable frequency dividing network, having the advantageous characteristic that failure of the input signal causes zero output rather than an erroneous output frequency. Such a device is useful in a wide variety of applications, including frequency standards, television sweep and synchronizing pulse generators, etc.

Though the curves illustrating the operation of this invention have been shown only for the cases of Fig. 2, Fig. 3, Fig. 26, Fig. 29, Fig. 31, and Fig. 32 and only with a sinusoidal or amplitude modified input applied thereto and only with certain types of networks therein, it is obvious that other wave shapes can be employed as input waves, and that other networks can be employed, dependent upon the translation of wave shape required between input and output. Likewise, it is apparent that in certain cases it is desirable to employ the invention as illustrated in Figs. 4 and 5, with or without an input signal applied thereto.

I claim:

1. A wave distorting system comprising a phase modifier having four inputs and one output, means for supplying one input with potential waves to be phase modified, means for supplying the remaining three inputs with modifying potential waves, said system having means in each of said remaining inputs for retarding the phase of a potential in proportion to the modifying potential, a transmission network between said first input and the second input for supplying modifying potentials derived from the voltage waves supplied to said first input, transmission networks between the output of said phase modifier and the remaining two inputs for supplying modifying potentials derived from the output of said phase modifier, said output wave being substantially different from the input wave and not being an amplified form thereof.

2. A wave distorting system comprising a phase

modifier having three inputs and one output, means for supplying one of said inputs with potential waves to be phase modified, means for supplying the remaining inputs with modifying potentials, said phase modifier having means for retarding the phase of a potential in said first input by an amount proportional to the potential on said remaining inputs, a transmission network between the first input and one of said remaining inputs and a transmission network between the output and the free input, said output wave being substantially different from the input wave and not being an amplified form thereof.

3. A wave distorting system having substantial sensitivity, said system comprising a phase modifier having three inputs, means for supplying signals to be distorted to one input, means for supplying modifying signals to a second input at a suitable amplitude so that said phase modifier provides a phase shift of less than 90 degrees for maximum modifying signals, and feedback means from the output to said third input, said feedback means providing a gain of between .5 and 1 and a phase shift of between zero and 90 degrees, said output wave being substantially different from the input wave and not being an amplified form thereof.

4. A wave distorting system having substantial sensitivity comprising a phase modifier having three inputs, means for supplying signals to be distorted to one input, means for supplying modifying signals to a second input at a suitable amplitude so that said modifier provides a phase shift of less than 90 degrees for maximum modifying signals, and feedback from the output to said third input, said feedback means providing a gain of between one and two and a phase shift of between 180 and 270 degrees, said output wave being substantially different from the input wave and not being an amplified form thereof.

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