Dec. 28, 1954 E. L. KENT 2,697,959

APPARATUS FOR PRODUCING COMPLEX WAVES AT A DESIRED FREQUENCY

Filed Nov. 23, 1951 2 Sheets-Sheet 1

Fig. 1

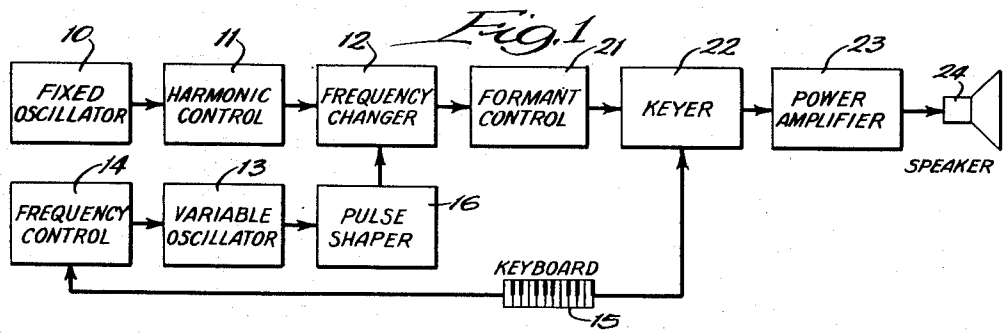
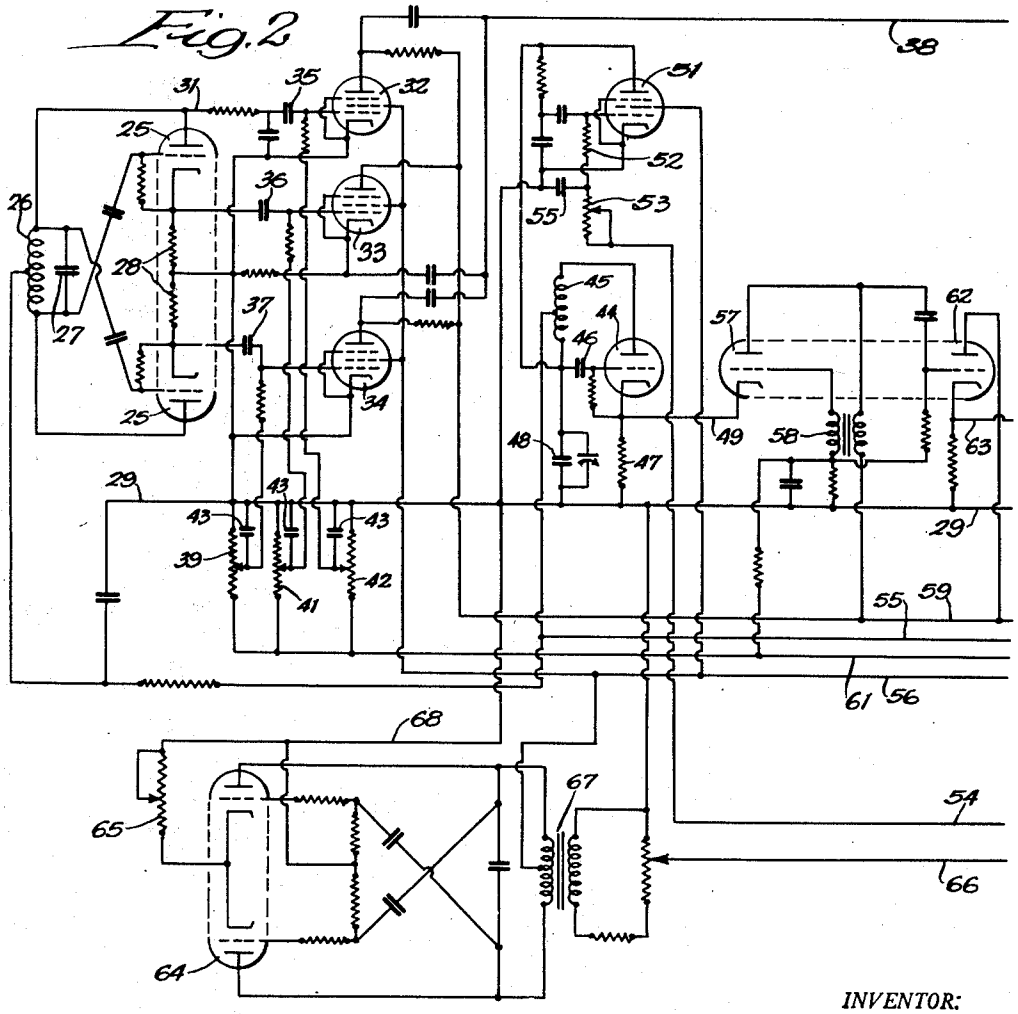


Fig. 2



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Fig. 2A

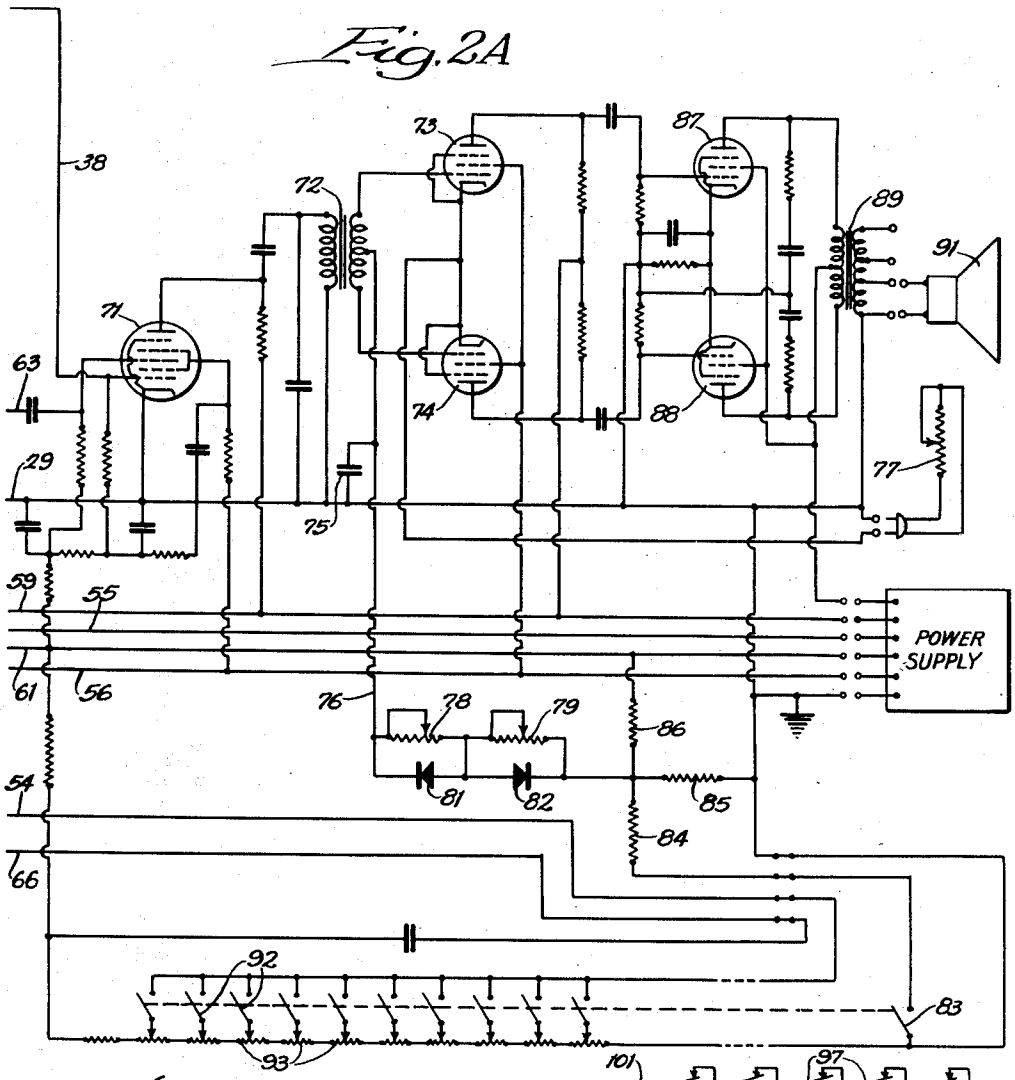


Fig. 3

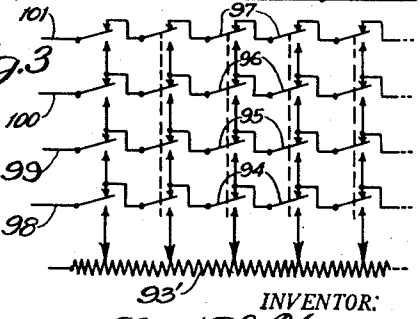


Fig. 4

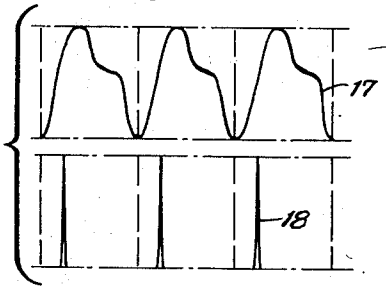
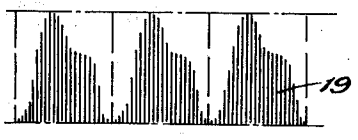


Fig. 5



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APPARATUS FOR PRODUCING COMPLEX WAVES AT A DESIRED FREQUENCY

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Application November 23, 1951, Serial No. 257,820

15 Claims. (Cl. 84—1.22)

This invention relates to a method of and apparatus for producing complex waves at a desired frequency and more specifically to the production of musical tones.

The generation of complex waves at different frequencies for musical or other purposes has heretofore generally been accomplished by synthesis; that is, by mixing in the desired relative amplitudes a plurality of sine waves of different frequencies or by using a different complex wave generator for each different frequency desired. Both types of generation are used in electronic organs as now being manufactured.

A far simpler and in many ways a more versatile and flexible method of generating complex waves would be to generate a single complex wave of the desired wave form at a fixed frequency and to change its frequency as desired. One difficulty with this type of operation has been that no satisfactory frequency changer has been available which will change the fundamental frequency of the wave without altering its wave form.

Mechanical frequency changers have been proposed and can accomplish a change in frequency while maintaining wave form. However due to mechanical inertial effects such devices are not satisfactory since they can not effect sufficiently rapid changes in frequency for musical purposes.

Frequency changers as generally used in vacuum tube circuits are of two classes. One class includes multipliers and dividers which multiply or divide the fundamental frequency into integral multiples or divisors of the original wave frequency. The other class includes changers which add a single number to each frequency in the original wave. Neither of these classes of frequency changer is capable of maintaining the original wave form and they are therefore not satisfactory for musical work.

In this connection it is to be noted that two waves may have similar harmonic contact from the standpoint of amplitude of the harmonics or partials but may still be of dissimilar form because of different phase relationships between the harmonics. Even though the ear can not detect phase differences the peak value of a tone signal is controlled by the phase angle between the harmonics and in many cases unless the phase is properly controlled excessive peak levels might result with consequent overloading of the circuit or of the ear of a listener. It is therefore desirable to maintain the signal peak values at a minimum by maintaining the optimum phase relationship of the waves making up the signal.

It is one of the objectives of the present invention to provide a frequency changing method and apparatus in which the frequency of a complex wave is changed without changing the wave form.

Another object is to provide a frequency changing method and apparatus in which a complex wave at a frequency higher than that desired is electrically scanned or sampled to produce a series of pulses whose amplitudes are proportional to the instantaneous amplitudes of the original wave at progressively different phase positions. The envelope of such a series of pulses is a wave of the same form as the original wave and at a frequency equal to the difference between the frequency of the original wave and the effective scanning or sampling frequency.

It is to be observed that pulses spaced to sample or scan the original wave may be produced by generating the pulses in the same frequency as the original wave and progressively shifting their phase position or by generating the pulses at a different frequency. The effective or apparent frequency of the pulses in either case will be different than the frequency of the original wave. In both cases the effective pulse frequency is preferably

controllable to change the frequency or pitch of the output wave.

Still another object of the invention is to provide a method of and apparatus for producing musical tones in which a complex wave of the desired form is generated at a fixed frequency and has its frequency changed to the desired pitch value without changing its form and is then utilized to operate a transducer such as a loud speaker.

A still further object is to provide a method of and apparatus for producing a musical tone in which the scanning or frequency changing circuit is connected to the transducer through keying tubes controlled by key switches.

According to one feature of the invention the frequency of the pulse generator is controlled by switches operated in sequences with the keying switches so that a wave of the desired pitch is produced and is then keyed to the transducer.

A further object is to provide a method of and apparatus for producing musical tones in which a low frequency tremolo generator is connected to the pulse generator to vary its frequency in a relatively slow cycle thereby to produce a tremolo effect.

A still further object is to provide a method of and apparatus for producing musical tones in which slurring or glissando effects are produced by controlling the rate of change of the frequency of the pulse generator. In a preferred construction the frequency of the pulse generator is controlled by a variable reactance device which in turn is controlled through a variable controlled voltage circuit including adjustable time delay elements to control the rate of change of the reactance.

A still further object is to provide a method of and apparatus for producing musical tones in which the attack and decay characteristics of the tones are controlled in the keying circuit through parallel controlled circuits each including a variable impedance and a rectifier with the rectifiers in the different circuits arranged to pass current in opposite directions.

The above and other objects and features of the invention will be more readily apparent from the following description when read in connection with accompanying drawings in which

Figure 1 is a block diagram of an apparatus for producing musical tones according to the invention;

Figures 2 and 2A taken together, are a wiring diagram of the apparatus;

Figure 3 is a partial diagram showing a key circuit for multiple channel operation;

Figure 4 is a graph showing a typical complex wave and a pulse wave for scanning or sampling the same; and

Figure 5 is a graph showing the resulting wave.

As illustrated in the block diagram Figure 1, the apparatus comprising a fixed oscillator **10** which may be any desired type of generator of electrical waves and which will preferably generate complex waves at a fixed frequency. The frequency of such waves is higher than the frequency of the highest desired musical tone and for musical work is preferably on the order of 30 kilocycles. The generated waves are passed through a harmonic control device **11** which may control the harmonic values in the wave to produce a wave corresponding in shape to the desired musical tone. The output of the harmonic control device is an electric wave at the generated frequency and whose wave form corresponds to the desired wave shape. This wave is supplied to a frequency changer or scanning device **12**.

At the same time a variable frequency pulse wave is generated by a variable oscillator **13**. The frequency of the oscillator is controlled by a frequency control device **14** connected to the oscillator and which is in turn controlled by the operator as desired. As shown in the diagram the frequency control device **14** is connected to a keyboard **15** through which it is controlled in turn to control the frequency of the variable oscillator **13**. The output of the variable oscillator may be used as generated if it is a sharp pulse but is preferably passed through a pulse shaper **16** wherein the pulses are sharpened to form a series of spaced very short sharp pulses which are supplied to the frequency changer,

The generated electrical wave as supplied to the frequency changer by the harmonic control device may take a form such as that shown at **17** in Figure 4. The pulses supplied to the frequency changer by the pulse shaper **16** are very short sharp pulses such as indicated at **18** in Figure 4. The pulses are at a different frequency than the wave and function to sample or scan the wave at progressively different phase positions so that the output of the frequency changer will comprise a series of short sharp pulses as indicated at **19** in Figure 5. The amplitude of the pulses **19** will be proportional to the instantaneous amplitude of the wave **17** at phase positions therein corresponding to the phase positions of the pulses **18**. The frequency of the envelope of the pulses **19** will be equal to the difference in frequencies of the waves **17** and the pulses **18**. Thus if the wave **17** has a frequency of 30 kilocycles and the pulses **18** have a frequency of 29,560 cycles the envelope of the pulses **19** will have a fundamental frequency of 440 cycles corresponding to standard A.

The pulses **19** are supplied to a formant control **21** which may be one or more resonant circuits to shape the pulse wave to correspond to desired musical sounds. The wave passed by the formant control is supplied through a keyer **22** and a power amplifier **23** to a loud speaker **24**. The tone produced by the loud speaker will therefore correspond to the wave shape of the original wave **17** as modified by the formant control when it is used and will have a fundamental frequency in the example stated of 440 cycles. The block diagram of Figure 1 illustrates one complete channel but it will be understood that a complete instrument might include several such channels each producing a different desired type of tone.

In the circuit illustrated in Figure 2 the fixed oscillator **10** is shown as a Hartley type oscillator arranged in push-pull. The oscillator includes a double tube **25** with the anodes of both sections connected through a tank circuit including an inductance **26** and a condenser **27**. The opposite ends of the tank circuit are cross connected to the grids of the control sections and the cathodes are interconnected through resistors **28** the mid point of which is connected to a ground line **29**. In this circuit sine waves are derived from the tank circuit through a connection **31** and pulse waves may be derived from the cathode sections. When a single cathode section is used a pulse wave similar in form to a standard string tone is produced while when waves are derived from both cathode sections in push pull the resulting wave is similar in form to a wood wind tone.

The outputs from the fixed oscillator section are supplied to the harmonic control section which, as shown, includes three mixer tubes **32, 33** and **34**. The tube **32** has its control grid connected through a blocking condenser **35** to the output lead **31** to receive the sine wave oscillations. The tube **33** has its control grid connected through a blocking condenser **36** to the cathode of the upper oscillator tube section to receive oscillations therefrom and the control grid of the tube **34** is similarly connected through a blocking condenser **37** to the cathode of the lower oscillator tube section. The anodes of the tubes **32** and **34** and the cathode of the tube **33** are connected to a common output line **38** which goes to the frequency changer or scanning section.

To control the strengths of the different signals from the mixer tubes the grids thereof are connected through adjustable resistors **39, 41** and **42** to the ground line **29** and have condensers **43** in parallel with the resistor sections. By adjusting the resistors the amplitude of the signals passed by the several tubes can be controlled so that the different types of signals are supplied to the output line **38** in the desired relative strengths to produce the desired wave form.

The variable oscillator as shown at **13** in the block diagram is illustrated as comprising a vacuum tube **44** whose anode and grid are interconnected through a coil **45** and a condenser **46**. The cathode of the tube is connected to ground through a resistor **47** and the grid is connected to ground through an adjustable condenser circuit **48**. Pulse waves are derived from the cathode of the oscillator circuit through a line **49**.

To vary the frequency of the oscillator the grid thereof is connected through a variable reactance circuit to ground. This circuit as shown comprises a vacuum tube

51 whose anode is connected to the grid of the oscillator tube **44** and whose control grid is connected through a fixed resistor **52** and a variable resistor **53** to a control circuit **54**. A condenser **55** is connected with the resistor **53** to form therewith a variable time delay circuit which can be adjusted to vary the rate of change of voltage on the control grid. By adjusting the resistor **53** the desired slurring or glissando effects can be produced. At the same time the voltage supplied to the control grid of the tube **51** will control its effective reactance and will thereby control the frequency of oscillation of the oscillator tube **44**. Power is supplied to the oscillator **44** as well as to the oscillator **25** through a line **55** leading from a suitable power source as described more fully hereinafter. Screen grid voltage for the variable reactor tube **51** and for the mixer tubes **32, 33** and **34** is supplied by a line **56** from a suitable power source.

The voltage pulses supplied by the oscillator **44** through the line **49** are supplied to the cathode of a blocking oscillator **57**. This oscillator has its grid plate circuit supplied with voltage from a transformer **58** which is connected to a line **59** leading to a suitable power source. The grid of the oscillator is supplied with negative bias from a line **61** connected to the power source so that it can oscillate only when it receives a pulse from the line **49**. After producing one cycle the oscillator immediately blocks itself by driving its grid more negative so that a very short pulse is produced once during each cycle of oscillating. These pulses are supplied to the control grid of a clipper section **62** which is biased in such a manner that only the peak values of the pulses will cause it to pass current. The clipped pulses are very short sharp pulses as indicated at **18** in Figure 4 and are supplied through a line **63** to the frequency changer or scanning unit.

To produce a tremolo effect a low frequency tremolo generator is provided connected to the variance reactor tube **51**. This generator as shown comprises a double ended vacuum tube **64** with its sections connected in push pull and having an adjustable resistor **65** in its cathode circuit by which its frequency can be adjusted. Power is supplied to the tremolo oscillator through a line **66** and a transformer **67** through which the oscillator can be keyed to operate only when desired. Oscillations produced by the tremolo oscillator are supplied through a line **68** to the control grid of the variable reactance tube **51** and will cause the reactance thereof to vary in a relatively slow cycle to produce a slow cyclic frequency change. This type of operation produces a very satisfactory tremolo or vibrato effect. The wave supplied by the harmonic control section to the line **38** and the pulse supplied from the clipper section **62** to the line **63** are fed to two separate control grids of a frequency changer or scanning tube **71**. The tube **71** is biased normally to cut off by connection of the control grid to which the line **63** is connected to the negative bias line **61** so that the tube is normally nonconducting except when a pulse is supplied through the line **63**. When a complex wave is present and pulses are being supplied from the clipper section the tube **71** will conduct each time a pulse is present and its output will be a short pulse whose amplitude is equal to the product of the amplitudes of the supplied pulse and the complex wave. Thus the tube **71** will have as its output pulses such as shown at **19** in Figure 5 whose frequency is equal to the frequency of the supplied pulses and whose amplitudes are proportional to the instantaneous amplitudes of the complex wave. The tube **71** therefore samples or scans the complex wave at the frequency of the supplied pulses and the envelope of the output pulses **19** will have the same shape as the complex wave and a frequency equal to the difference between the complex wave frequency and the pulse frequency. Since the pulse frequency can easily be changed the output of the frequency changer or scanning section can change very rapidly without interfering in any way with the original wave form.

The pulses from the tube **71** are supplied to the primary winding of a transformer **72** whose secondary winding forms the input section of a pair of keying tubes **73** and **74**. The secondary of the transformer **72** is center tapped and connected through a condenser **75** to ground and to a key circuit **76**. The ends of the secondary are connected to the control grids of the tubes **73** and **74** and

the cathodes of these tubes are connected to ground through a variable resistor 77 forming an overall volume control for the device.

The tubes 73 and 74 are normally nonconducting due to connection of the circuit 76 to the negative bias line 61 as shown. In order to control attack and decay characteristics this circuit includes a pair of variable resistors 78 and 79 which are connected in parallel with rectifiers 81 and 82 to form in effect parallel circuit which will pass currents in opposite directions. To make the tubes 73 and 74 conducting, the bias is shunted through a key switch 83 and a resistor 84. A shunt resistor 85 is provided across the key circuit and has a high value relative to the resistor 84 and also relative to a resistor 86 in series in the bias connection. In one example the resistor 84 may be 1,000 ohms, the resistor 85 may be 28,000 ohms and the resistor 86 may be 14,000 ohms. When the switch is open, negative bias will build up on the grids of the tubes 73 and 74 to make them nonconducting. When the switch 83 is closed, ground potential will build up on the grids through the resistor 79 and rectifier 81 until the tubes become conducting. The rate of change of the bias can be adjusted through the resistor 79 to vary the attack characteristic of the tone. When the switch 83 is again open negative bias will build up on the tube grids through the resistor 78 and rectifier 82 which determine the rate of build up of bias and therefore the decay of the tones. Through these circuits both attack and decay can be separately controlled with the use of a single key switch so that the device lends itself to a very simple keying such as might be performed by a mechanical playing device like a standard player piano roll.

The output of the keying tubes is supplied to a power amplifier shown as comprising a pair of tubes 87 and 88 connected in push pull. The output of the power amplifier section supplies the primary of a transformer 89 to which a loud speaker 91 may be connected. As shown the secondary of the transformer is formed with a plurality of taps to which the loud speaker can be selectively connected to adjust the range of driving voltage.

In this circuit oscillations at a high frequency and of the desired wave form are produced in the main oscillator 25 and are given the wave form corresponding to the desired musical tone in the harmonic control section. These waves at a high frequency are then scanned or sampled in the frequency changer section whose output is a wave of the desired wave form and the desired controlled frequency. This wave is keyed to the output amplifier and the loud speaker through keying sections in which attack and release are easily controlled. By simple adjustments of the several adjustable elements including resistors 39, 41 and 42, the wave form can easily be controlled. Adjustment of the resistor 53 controls the slurring and glissando effects and adjustment of the resistor 65 controls the frequency of the tremolo which is supplied. Numerous musical effects simulating known effects can therefore easily be produced and by adjusting the various elements of the circuit novel musical effects can be obtained. It will be noted in this connection that the frequency of the pulse generator can be controlled either continuously or through step by step keying as desired.

As illustrated the pulse generator is adapted to be keyed for which purpose the line 54 is connected to ground through any one of a series of key switches 92 which introduce varying amounts of resistance 93 into the circuit. The switches 92 may be operated through a keyboard such as shown at 15 in Figure 1 and are preferably arranged to be operated in sequence with the keying switch 83 or with a plurality of such switches connected in parallel. For example, the keys may be arranged so that when they are depressed they will first close one of the switches 92 to select the desired frequency and will thereafter close the keying switch 83 to transmit the selected frequency to the loud speaker. If desired, the keying switches may be arranged for mechanical operation leaving the performer free to adjust the various circuit controls to produce varying musical effects.

For multiple channel operation through a single keyboard an arrangement of switches such as shown in Figure 3 may be employed. This figure illustrates a resistor 93' corresponding to the resistors 93 as shown in Figure 2A having a series of points therein tapped. Each tapped point is connected to one point of a double throw switch 94 forming one of a series of four gang switches 95, 96 and 97 corresponding to each key.

With this construction when any one of the keys is depressed the point on the resistor corresponding thereto will be connected to the lowermost of the four output channels 98, 99, 100 and 101, which correspond to the line 54 of four different tone generating units. If more than one key is depressed simultaneously, the left hand key will be connected to the lower channel 98 and the keys progressively to the right therefrom will be connected to the upper channels in progressive order. In this way a plurality of different channels can be controlled through a single keyboard in a simple manner.

While one embodiment of the invention has been shown and described in detail it will be understood that this is illustrative only and is not to be taken as a definition of the scope of the invention reference being had for this purpose to the appended claims.

What is claimed:

1. Apparatus for producing musical tones comprising a generator of electrical waves of the same wave form as the desired musical tones and of a frequency higher than the frequency of the highest desired musical tone, an electrical scanning circuit connected to the generator, a pulse generator producing a series of short electrical pulses which are progressively spaced to correspond to different phase positions relative to the electrical wave, a connection from the pulse generator to the scanning circuit to energize the scanning circuit each time a pulse is supplied thereto so that the scanning circuit will produce a series of pulses corresponding to the instantaneous amplitudes of the wave at spaced phase positions, and a transducer connected to the scanning circuit to convert the last named series of pulses into musical tones.

2. Apparatus for producing musical tones comprising a generator of electrical waves of the same wave form as the desired musical tones and of a frequency higher than the frequency of the highest desired musical tone, a pulse generator producing a series of short electrical pulses at a different frequency than the electrical wave, a frequency changer circuit connected to both of the generators to be energized by said pulses thereby to produce a series of electrical pulses corresponding in frequency to the generated pulses and in amplitude to the instantaneous amplitude of the electrical wave, and a transducer connected to the frequency changer circuit to convert the last named series of pulses into musical tones.

3. Apparatus for producing musical tones comprising a generator of electrical waves of the same wave form as the desired musical tones and of a frequency higher than the frequency of the highest desired musical tone, a pulse generator producing a series of short electrical pulses at a different frequency than the electrical wave, a frequency changer circuit connected to both of the generators to be energized by said pulses thereby to produce a series of electrical pulses corresponding in frequency to the generated pulses and in amplitude to the instantaneous amplitude of the electrical wave, a transducer, and a keying circuit connecting the frequency changer circuit to the transducer.

4. Apparatus for producing musical tones comprising a generator of electrical waves of the same wave form as the desired musical tones and of a frequency higher than the frequency of the highest desired musical tone, a pulse generator producing a series of short electrical pulses at a different frequency than the electrical wave, a frequency changer circuit connected to both of the generators to be energized by said pulses thereby to produce a series of electrical pulses corresponding in frequency to the generated pulses and in amplitude to the instantaneous amplitude of the electrical wave, a circuit including a first switch connected to the pulse generator to energize it, a transducer, a keying circuit including a control switch, and a key connected to the switches to operate them in predetermined sequence.

5. Apparatus for producing musical tones comprising a generator of electrical waves of the same wave form as the desired musical tones and of a frequency higher than the frequency of the highest desired musical tone, a pulse generator producing a series of short electrical pulses, a variable reactance device connected to the pulse generator to vary the frequency of the pulses, a frequency changer circuit connected to both of the gen-

erators to produce a series of electrical pulses of the same frequency of the generated pulses and of amplitudes corresponding to the instantaneous amplitudes of the wave at different phase positions, a transducer connected to the frequency changer circuit, and control means to control the reactance of said variable reactance device.

6. Apparatus for producing musical tones comprising a generator of electrical waves of the same wave form as the desired musical tones and of a frequency higher than the frequency of the highest desired musical tone, a pulse generator producing a series of short electrical pulses, a variable reactance device connected to the pulse generator to vary the frequency of the pulses, a frequency changer circuit connected to both of the generators to produce a series of electrical pulses of the same frequency of the generated pulses and of amplitudes corresponding to the instantaneous amplitudes of the wave at different phase positions, a transducer, a keying circuit including a controlling switch to connect the transducer to the frequency changer circuit, a circuit including a controlling switch to control the reactance of said variable reactance device, and key means to operate said switches in predetermined sequence.

7. Apparatus for producing musical tones comprising a generator of electrical waves of the same wave form as the desired musical tones and of a frequency higher than the frequency of the highest desired musical tone, a pulse generator producing a series of short electrical pulses, a variable reactance device connected to the pulse generator to vary the frequency of the pulses, a frequency changer circuit connected to both of the generators to produce a series of electrical pulses of the same frequency of the generated pulses and of amplitudes corresponding to the instantaneous amplitudes of the wave at different phase positions, a transducer, a keying circuit including a controlling switch to connect the transducer to the frequency changer circuit, a control circuit for the variable reactance device including a plurality of selectively operable switches to produce different reactance, and keying means selectively to close the last named switches and then to close the controlling switch.

8. Apparatus for producing musical tones comprising a generator of electrical waves of the same wave form as the desired musical tones and of a frequency higher than the frequency of the highest desired musical tone, a frequency changer circuit connected to the generator to reduce the frequency of said wave without altering its wave form, a transducer, a circuit including an electron discharge tube connecting the frequency changer circuit to the transducer, a bias source connected to the tube normally biasing it to cut off, a control switch for the tube to remove the bias therefrom so that the tube will conduct, a pair of parallel circuits in the connection from the tube to the bias source, and a variable impedance and a rectifier in each of said circuits with the rectifier set to pass current in opposite directions.

9. Apparatus for producing musical tones comprising a tone generating means to producing an electric wave corresponding to the desired musical tone, a transducer, a circuit including an electron discharge tube connecting the generating means to the transducer, a bias source, a pair of parallel circuits connecting the bias source to the tube normally to bias the tube to cutoff, each of said circuits including a variable impedance and a rectifier and the rectifiers set to pass current in different directions in the different circuits, and a control switch to shunt the bias source to make the tube conduct.

10. Apparatus for producing musical tones comprising a generator of electrical waves of the same wave form as the desired musical tones but of a frequency higher than that of the highest desired tone, a frequency changer circuit connected to the generator, a pulse generator producing a series of short electrical pulses of a different frequency than the electrical wave, a connection from the pulse generator to the frequency changer circuit to supply pulses thereto so that the frequency changer circuit will produce a series of pulses whose amplitudes correspond to the instantaneous amplitudes of the wave at different phase positions, a control element for the pulse generator to control the pulse frequency, and a low frequency tremolo generator connected to the control element to produce a low frequency variation in the pulse frequency.

11. Apparatus for producing musical tones comprising a generator of electrical waves of the same wave form as the desired musical tones but of a frequency higher than that of the highest desired tone, a frequency changer circuit connected to the generator, a pulse generator producing a series of short electrical pulses of a different frequency than the electrical wave, a connection from the pulse generator to the frequency changer circuit to supply pulses thereto so that the frequency changer circuit will produce a series of pulses whose amplitudes correspond to the instantaneous amplitudes of the wave at different phase positions, a variable reactance device connected to the pulse generator to vary its frequency, and a low frequency tremolo generator connected to the variable reactance device to control it.

12. Apparatus for producing musical tones comprising a generator of electrical waves of the same wave form as the desired musical tones but of a frequency higher than that of the highest desired tone, a frequency changer circuit connected to the generator, a pulse generator producing a series of short electrical pulses of a different frequency than the electrical wave, a connection from the pulse generator to the frequency changer circuit to supply pulses thereto so that the frequency changer circuit will produce a series of pulses whose amplitudes correspond to the instantaneous amplitudes of the wave at different phase positions, a control element for the pulse generator to control the pulse frequency, a control circuit connected to the control element to change the effect thereof, and adjustable time delay elements in the control circuit to control the rate of change of the pulse frequency.

13. Apparatus for producing musical tones comprising a generator of electrical waves of the same wave form as the desired musical tones but of a frequency higher than that of the highest desired tone, a frequency changer circuit connected to the generator, a pulse generator producing a series of short electrical pulses of a different frequency than the electrical wave, a connection from the pulse generator to the frequency changer circuit to supply pulses thereto so that the frequency changer circuit will produce a series of pulses whose amplitudes correspond to the instantaneous amplitudes of the wave at different phase positions, a variable reactance device connected to the pulse generator to vary the pulse frequency and whose reactance varies in response to a control voltage, a control circuit connected to the variable reactance device to supply a variable control voltage thereto, and adjustable impedance elements in the control circuit to control the rate of change of control voltage.

14. Apparatus for producing complex waves at a desired frequency comprising a generator of electrical waves of the desired complex form and of a frequency higher than the desired frequency, a frequency changer circuit connected to the generator, a pulse generator producing a series of short electrical pulses at a frequency different than the frequency of the electrical wave, and a connection from the pulse generator to the frequency changer circuit whereby the pulse generator will cause the frequency changer circuit to produce a series of pulses at the same frequency as the generated pulses and whose amplitudes correspond to the instantaneous amplitudes of the electrical wave at different phase positions.

15. Apparatus for producing musical tones including in combination, means for providing tone currents, a transducer, a circuit connecting said means to said transducer including an electron discharge valve having a control element, said circuit supplying tone currents to said transducer in accordance with the voltage applied to said control element thereof, means for providing a control voltage, and a control circuit including a keying switch selectively connecting said control voltage to said control element, said control circuit including a pair of oppositely poled rectifiers connected in series and a pair of time delay impedances in shunt with said rectifiers to control the attack and decay characteristics of the tone currents applied to said transducer.

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