

March 17, 1942.

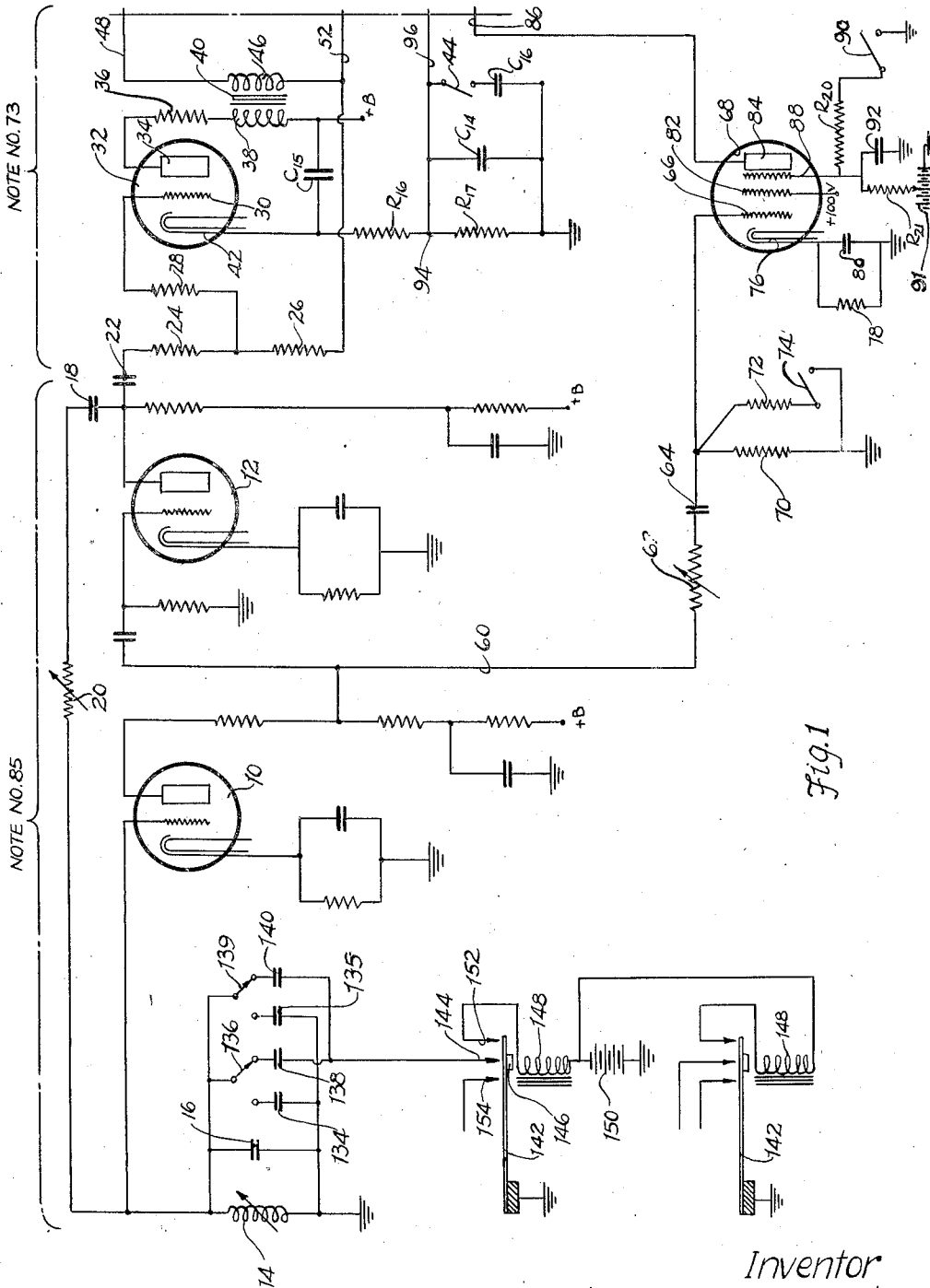
L. HAMMOND

2,276,389

ELECTRICAL MUSICAL INSTRUMENT

Filed April 2, 1938

3 Sheets-Sheet 1



Inventor
Laurens Hammond
By *Williams, Bradbury, McClellan & Hinkle*
Attorneys

March 17, 1942.

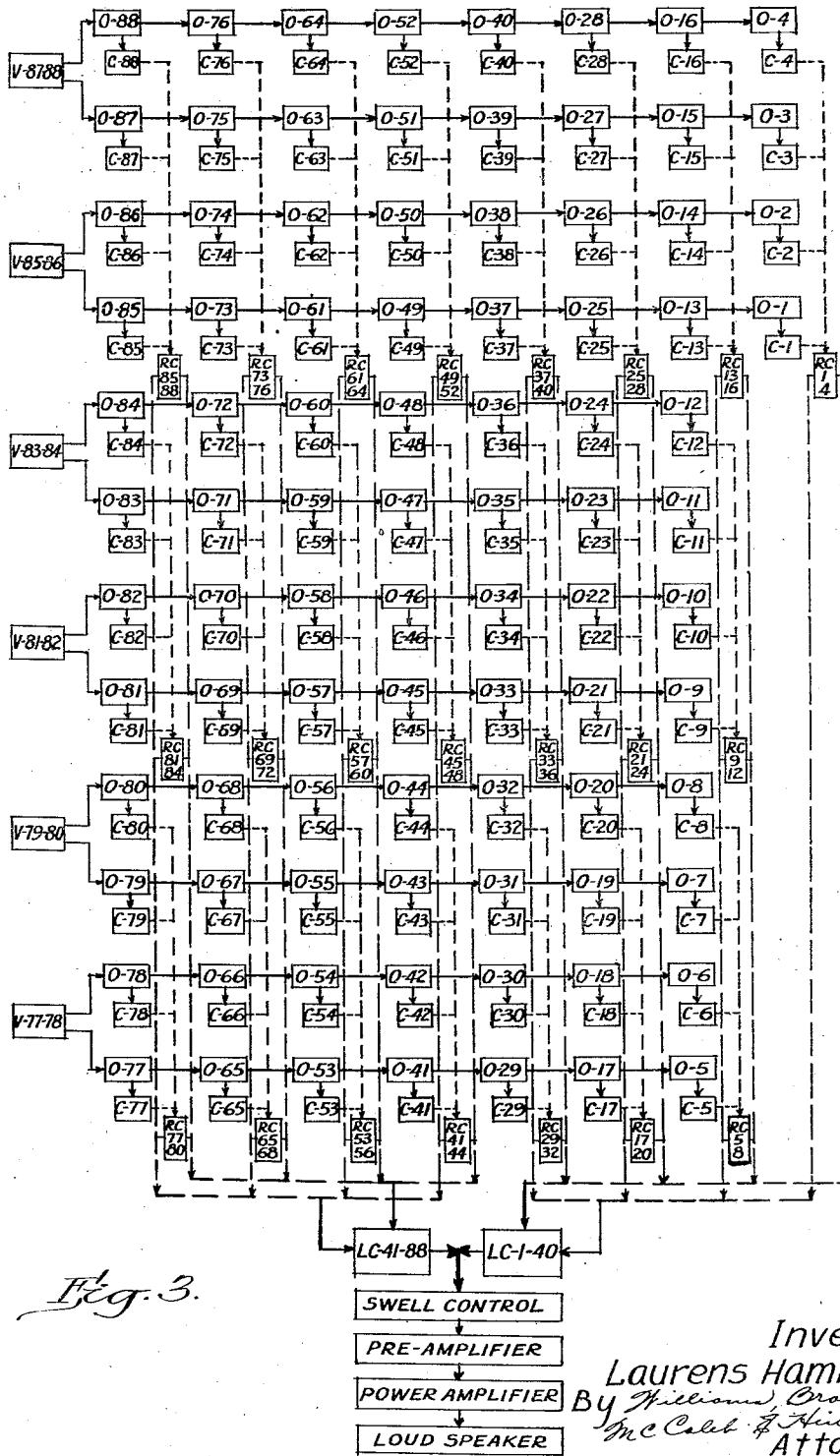
L. HAMMOND

2,276,389

ELECTRICAL MUSICAL INSTRUMENT

Filed April 2, 1938

3 Sheets-Sheet 3



UNITED STATES PATENT OFFICE

2,276,389

ELECTRICAL MUSICAL INSTRUMENT

Laurens Hammond, Chicago, Ill.

Application April 2, 1938, Serial No. 199,612

15 Claims. (Cl. 84—1.25)

My invention relates generally to electrical musical instruments, and more particularly to a system for generating electrical impulses of the frequencies of the musical scale by purely electrical means.

It has been proposed in the past to obtain the electrical impulses of the various frequencies required for an electrical musical instrument from oscillators, one for each note of the scale. Generally speaking, such systems have not proved satisfactory due to the difficulty of maintaining the oscillators exactly in tune with one another. In an instrument of the piano type, it is necessary to provide 88 such oscillators, and the difficulty of tuning such a large number of oscillators is very great, when the fact is taken into consideration that the frequency of oscillation of the oscillation generators may change considerably with the slight changes in the characteristics of the tubes and other circuit elements due to aging and to atmospheric conditions as well as to changes in the voltage of the power supply.

Of course oscillators may be made more stable, with reference to the frequency of oscillation, by various means, but such means usually add materially to the complication and cost of the oscillator, and since in a piano type of instrument it would be necessary to provide 88 such oscillators, the complexity and cost of the system is multiplied so as to render impractical a system in which an individual and independently tunable oscillator is employed for each note.

To overcome these defects and disadvantages, I have provided a system employing twelve master oscillators, one for each of the notes of the highest octave of the instrument. Since there are only twelve of these master oscillators, it is practical to make them of good quality so that their frequencies will be very stable. Each of the twelve master oscillators is connected in cascade with a series of relaxation oscillators, one for each of the corresponding octave notes in the lower octaves. For example, the master oscillator for the generation of the frequency required for the note A of the highest octave will be connected to the relaxation oscillator for the note A of the second highest octave, and the latter will be connected to the relaxation oscillator for the note A in the third highest octave, etc. Thus, all of the oscillators for the notes A of the instrument will be connected in a cascaded series and each oscillator in the series will have its frequency stabilized by the oscillator for the note which is one octave higher and which

therefore generates a frequency twice that of the oscillator which is controlled thereby.

In a system of this character, a variation in the frequency of oscillation of the master oscillator will cause a corresponding variation in the frequencies of oscillation of each of the other oscillators which is connected in cascaded series with such master oscillator. For example, the master oscillator for the generation of a frequency of the note A of the highest octave will, if tuned to the pitch A—440, oscillate at a frequency of 3520 C. P. S. If the tuning of this master oscillator is changed so that instead of oscillating at 3520 it oscillates at 3522 C. P. S., the relaxation oscillator for the generation of the note A of the second highest octave will be controlled by the master oscillator so as to generate a frequency exactly one half of the frequency of the master oscillator, namely, 1761 C. P. S. Similarly, the frequencies generated by the oscillators for the notes A in the lower octaves will each be proportionately increased. It is therefore possible, by accurately tuning the twelve master oscillators, to tune all of the remaining oscillators.

Furthermore, if the frequency of oscillation of the master oscillator is periodically shifted at a vibrato frequency rate, the frequencies of oscillation of the relaxation oscillators controlled by such master oscillator will be shifted correspondingly. Thus it is possible to provide a very simple and effective means to produce vibrato effects in an instrument employing the generating system of my invention.

Inasmuch as the subject of the causes and effects of vibrato in a musical instrument are not widely known, the underlying principles of vibrato in a musical tone will be briefly discussed.

Strictly speaking, a vibrato is the musical result obtained by periodically changing the frequency of the tone being sounded through a relatively narrow range of pitch change, at a periodic rate in the order of 7 C. P. S. The periodic change in frequency is normally not sufficiently great to give the effect of actual pitch change but rather to give the effect of warmth of tone. The instrument upon which the effect of vibrato is most frequently heard and most easily recognizable is the violin. The vibrato effect is not, however, a feature exclusively of the violin tone. It is present in the tones of many other musical instruments although it is probably not as readily recognized in the tones of other instruments. For example, when chords are played upon a piano, there is a pronounced

vibrato, although it is seldom recognized as such by the average listener. This characteristic of the tone of the standard piano is resultant from the fact that the tone of the piano note, especially in the lower register, is made up of a fundamental and long series of partials.

A further characteristic of the standard piano lies in the fact that the tone of a piano note, especially in the lower register, is made up of a fundamental and a long series of partials, which partials are not true harmonics of the fundamental—in the sense that they are of frequencies which are not exact integral multiples of the fundamental. This is due to the fact that whereas the string continues to generate sound over a considerable period of time, it is not continuously excited, but receives all of its energy during the blow of the hammer. If the string were an ideal one—that is to say, having no stiffness of its own, a uniformly distributed mass in a diameter which could be completely neglected by comparison with its length—then it could be shown that such a string would give rise to partials of frequencies which were exact harmonics of the fundamental. This is not the case in the standard piano as may quickly be shown by watching the pattern shown on a cathode ray oscillograph operated from a microphone picking up the sound of a piano note. If all the partials of the tone were exact harmonics, the shape of the pattern would not change appreciably during the decay of the note. Actual experiment will immediately show small amplitude high frequency waves which travel rapidly along on the wave produced by the lower frequencies.

Pianos are usually tuned by a beat system, and whereas the methods of tuning differ in detail, all of them tend to expand the musical scale in such a way that the highest notes of the scale are sharp and the lower notes are flat.

Let us assume therefore, that a piano has just been tuned in accordance with the best practice, and assume further, that double octaves are struck, for instance, A's Nos. 13, 25, 37 and 49. The second harmonic of the lowest A (13) is very close in frequency to the fundamental of the A (25) an octave higher. Similarly, the fourth harmonic of the A (13) is of a frequency in the vicinity of the fundamental of the A (37) two octaves higher, and in the vicinity of the second harmonic of the A (25) one octave higher. The eighth harmonic of the lowest A (13) is close in frequency to the fundamental of the A (49) three octaves up and close to the fourth harmonic of the A (25) one octave higher, and close to the second harmonic of the A (37) two octaves higher, etc. Now it is not possible to tune these four A's so that there will be no beats between them. Not only is it not possible to do so in a practical sense, but it is theoretically impossible as well. Without therefore considering the effects of the tempered musical scale which introduces beats in chords where notes of other than unison pitches are involved, it will be seen that beats will occur between frequencies which are close to one another and which are derived from the different notes of chords.

Further, beats are introduced for another reason. Except for the very lowest notes of the standard piano, either two or three strings are used for each note. The multiple strings cannot be tuned exactly alike as a practical matter, or even if they were, they would not remain so for very long after tuning. Chords played on a freshly tuned piano give rise to groups of frequencies

which are very close to one another but are not the same. The amounts of their differences are not of an order to suggest to the listener that the piano is out of tune, but these frequency differences play a very important part in characterizing the general effect and in giving "life" to the tone. This is due to the fact that when two frequencies which are close to one another are temporarily in phase with one another they reinforce each other, whereas when they are temporarily out of phase they tend to cancel one another. Thus, the acoustic spectrum is continuously changing—certain frequencies coming on while others are going off, etc. These effects are generally similar to the effect of a vibrato on a stringed instrument such as a violin.

In listening to the piano, one is ordinarily not aware of the vibrato effect because of the fact that a vibrato is associated in our minds with a definite simple rhythmical change such as is heard when a violinist rocks his finger on the string. In that case, he changes the effective length of the string in such a way as periodically to raise and lower the pitch. This is a change in frequency which, together with the pattern of the enclosure in which he is playing, produces at the listener's ears a change both in frequency and in intensity.

A simple vibrato on a melody instrument such as the violin occurs at a periodicity which may be counted by a listener. Depending on room conditions and other factors, this may sound very much like a tremulant to the listener, and there is no very clear difference, under some circumstances, between a vibrato, which is customarily thought of as a periodic change in frequency, and a tremulant, which is usually defined as a periodic change in intensity. The effect of the vibrato is enhanced by applying it at different frequencies to different notes, such that when a chord is played no definite rhythmic beating is perceptible. It may be stated in a general way, that when the listener becomes conscious of such rhythm to the extent that he is aware of the beat itself rather than of the effect of warmth which it gives to the tone, the effect is then unsatisfactory to many listeners. He is never able to count the vibrato effects of the piano and has therefore come to think of the piano as an instrument without vibrato, which is not the fact in a technical sense. Very strong vibrato effects are present in the standard piano, but they are of a very complex nature. The beats between the different frequencies do not last long because the notes decay, and there are a great many different rates of beat going on at the same time. To count them it is necessary to focus the attention on one particular beat and to start to count. Time does not permit much in this process, because before the rate is established clearly in the mind, the effect is gone.

In the instrument of my invention, I have a system for continuously shifting the frequencies of each note in a rhythmical manner. Thus, if a single note is played, the effect may be counted, if the attention is attracted to it, as is the case with the solo violin note. I provide a method, however, for putting a different vibrato rate on the different notes so that when chords are played there are many vibratos of different rates going on at the same time. This produces an effect too complex for the listener to analyze mentally—in the sense that he is unable to pick up these complex rhythms before they are gone. The shifting of the frequencies of different notes in a manner in which one is independent of another

produces a musical effect which is highly desirable. The complex tone of a chord, as in the standard piano, is then made up of many groups of frequencies which are shifting in audibility, so that some are growing more prominent while others are becoming less so.

It can be shown that a change in frequency such as is obtained in shifting the frequencies of the oscillators to produce a vibrato effect, ordinarily produces a slight change in the intensity of the note. Similarly, a tremulant device, which is considered primarily as a note intensity varying means ordinarily causes a change in the frequency of the note being sounded. Under certain circumstances there may be very little difference between the musical effect of a tremolo and that of a vibrato. Most musicians agree that the more desirable effect is that of the vibrato, or shift in frequency.

If the frequency of a note being sounded is periodically shifted at a vibrato rate, the effect (mathematically as well as musically) is not one particularly of frequency change, but rather the addition to the note of additional frequencies. The frequencies generated must, however, be multiples of the vibrato frequency. For example, if the fundamental frequency of the tone, before the vibrato was applied was 100 cycles, the second harmonic would have a frequency of 200 cycles. If a vibrato frequency of 7 cycles were then impressed upon the note, the resultant frequencies would have to be frequencies which are harmonics of the vibrato frequency of 7 cycles. Thus, the second harmonic, 200 cycles, in being modulated by the vibrato frequency of 7 cycles could not produce frequencies of 193 and 207 because these frequencies are not exact multiples of the vibrato frequency. Instead, the new frequencies produced upon modulation of the second harmonic of the tone by the vibrato frequency would be 196 and 203, the nearest harmonic frequencies of the vibrato frequency of 7 cycles. In addition to the frequencies of 196 and 203 cycles, there would be present in the tone, some energy at the frequencies of 189 cycles and 210 cycles, and other multiples of 7.

The vibrato effect in musical tones obtains its musical allure by virtue of the fact that by the introduction of a vibrato frequency a large number of frequencies are necessarily developed because of the modulation of the original tone frequency wave by vibrato frequency wave. The acoustical energy of the note being sounded will thus be distributed over a wide range of frequencies. Generally speaking, the human ear prefers such musical sounds in which the energy is widely distributed, to sounds in which the energy is concentrated at a single frequency or a limited number of frequencies. Tones in which the energy is distributed over a wide range have become recognized as the more beautiful, full and rich tones.

In the system of generating frequencies for musical instruments shown in this application, I have provided means for introducing vibrato frequencies, and this is accomplished by varying the frequency of oscillation of the twelve master oscillators periodically at vibrato frequency rates. I have also provided means for adjusting the range of the vibrato, so that the degree of effectiveness thereof may be varied to suit the character of the musical selection being rendered and to suit the individual taste of the performer.

It is thus an object of my invention to provide

an improved frequency generating system for electrical musical instruments.

It is a further object of my invention to provide an improved generating system for electrical musical instruments of the piano type wherein the frequency of the generators of all notes other than the twelve notes of the highest octave of the instrument are controlled by master oscillators oscillating at the frequencies of the twelve highest notes of the instrument.

A further object is to provide an improved electrical musical instrument having means for the generation of the necessary electrical frequencies which comprises relatively simple electrical circuits, and which may be economically manufactured.

A further object is to provide a frequency generating system for electrical musical instruments which will maintain the frequencies of oscillators over long periods of time and in which the tolerances in the electrical constants involved are relatively great.

A further object is to provide an improved frequency generating system for electrical musical instruments in which the frequency of oscillation may readily be varied to introduce a vibrato effect.

A further object of the invention is to provide an improved system of generation of the electrical frequencies required for an electrical musical instrument in which a series of generators may be readily tuned simultaneously.

Other objects will appear from the following description, reference being had to the drawings in which Figures 1 and 2 together constitute a wiring diagram of representative portions of an electrical musical instrument embodying my invention; and Figure 3 constitutes a diagrammatic representation of the elements of a complete instrument showing their functional relationship.

Referring to Figure 1, tubes 10 and 12, together with their associated circuits, constitute a master oscillator which may be assumed to be that of the note A of the highest octave of the instrument and generating the frequency of 3520 cycles. Although the oscillator is illustrated as comprising two separate tubes 10 and 12, these tubes will ordinarily be combined in a single twin triode tube. Tubes 10 and 12, together with their associated circuits, constitute an oscillator, the frequency of oscillation of which is determined primarily by the tuning circuit comprising a variable inductance 14 and a condenser 16 connected in parallel in the grid circuit of tube 10. The output of tube 10 is resistance coupled to the grid of tube 12 and the plate of tube 12 is connected to the grid of tube 10 by a feed-back circuit including a blocking condenser 18 and the variable resistance 20.

The signal in the output circuit of the tube 12 is transmitted through a blocking condenser 22 and coupling resistances 24, 26, and 28 to the grid 30 of a gas filled tube 32. The plate 34 of tube 32 is connected through a resistance 36 and the primary winding 38 of a transformer 40 with the positive terminal of the B current supply indicated in Fig. 1 as "-B." The cathode 42 of the tube 32 is connected through a high resistance R₁₅ and a relatively lower resistance R₁₇ to ground, to which of course the negative terminal of the B supply is also connected. A condenser C₁₅ is connected between the positive B supply and the cathode 42, and a condenser C₁₄ is connected in parallel with the resistance R₁₇ while a condenser C₁₆ is optionally connectable in paral-

1el with the resistance R_{17} by a manually operated switch 44.

The tube 32 and the circuits associated therewith constitutes a relaxation oscillator, the constants of which are such that it will normally oscillate at a frequency less than one half that of the frequency of the master oscillator comprising the tubes 10 and 12. If this relaxation oscillator did not have its grid connected to receive a signal from the master oscillator, its frequency of oscillation might vary slightly from its original frequency with changes in the characteristics of the tube due to aging, and with changes in temperature, humidity, and voltage of the supply. However, in view of the fact that the signal of the master oscillator is impressed upon the grid 20 of the tube 32, the frequency of oscillation of the relaxation oscillator is rigorously controlled so as to oscillate at a frequency exactly one half of that of the master oscillator. In other words, the rate at which the condenser C_{15} is charged through the resistances R_{16} and R_{17} is such that the potential difference between the cathode and plate is not sufficient to cause ionization of the gas in the tube until the time that the positive signal from the master oscillator is impressed upon the grid 30 of the tube 32.

The signal from the master oscillator raises the potential of the grid 30 sufficiently to cause discharge of the tube and as a result, the tube 32 is tripped by the signal from the master oscillator. It will be understood that only every other positive signal impulse received from the master oscillator and impressed upon the grid 30 is effective to cause discharge of the tube 32 because the charge on the condenser C_{15} , and hence the potential difference between the plate and cathode, is not sufficiently great at all times that the change in potential of the grid caused by the master oscillator signal will be sufficient to trip the tube. The constants of the circuits are such that only every other signal impulse from the master oscillator will be effective to trip the tube 32.

The discharge of the tube 32 causes a signal in the secondary 46 of the transformer 40 and the signal in the secondary is transmitted through conductor 48 and resistance 50 to the grid of the tube 32 forming part of the relaxation oscillator for the note A in the next lower octave. If the notes of a standard piano be numbered from 1 to 88 commencing with the lowest A as note No. 1, the note A of the highest octave will be numbered 85 and the note A of the second highest octave will be No. 73 and the A of the third highest octave will be note No. 61. In the drawings, the oscillators for these notes are appropriately numbered and designated by the dot and dash line brackets.

The relaxation oscillator for the note 61 is identical with that previously described for the note 73 except that the values of the constants of the circuit will be slightly different so as to cause the oscillator for the note 61 to have a normal frequency of oscillation less than 880 cycles. Since the tube 32 of the oscillator for note 73 will impress a signal upon the tube 32 of note 61 at 1760 cycles, it will be seen that every other positive signal impulse thus impressed upon the grid 32 for note 61 will be effective to cause discharge of the tube. Hence, the oscillator for the note 61 will generate its frequency of 880 cycles.

The oscillators for the notes Nos. 49, 37, 25, and 75

13 will be substantially identical with the oscillator for note No. 61, each oscillator receiving its stabilizing signal from the oscillator which generates a frequency twice as great. Since these oscillators are identical except for the constants of their circuits, they are not illustrated in Fig. 2, only the oscillator for note No. 1 being shown. The winding 38 for the oscillator for note No. 1 does not constitute part of a transformer, but is nevertheless included in this circuit since it is desirable that a certain amount of inductance be included in the plate circuit of the tube in order to improve the form of the wave.

The secondary windings 46 of the transformers 40, and the resistance 26 may be connected to a common conductor 52 to which a switch 54 is connected to enable this conductor normally to be connected to ground, but which may, for test purposes, be connected to a terminal 56 which is maintained at a potential slightly above or below ground by a suitable potential source indicated as a battery 58. If, for example, the switch 54 is connected to terminal 56 which is at a potential first of -6 volts and then +6 volts, and the tubes generate the proper signals, it will show that there is a sufficient factor of safety in the tube circuits to assure satisfactory operation over a long period. If, upon such test, it is found that some tubes do not deliver the proper signal, appropriate adjustments will be made in the tube circuits until this desired factor of safety is obtained.

The signal from the master oscillator for the note 85 is derived from the plate circuit of the tube 10 thereof through a conductor 60 which is connected through a variable resistance 62 and a blocking condenser 64, with the grid 66 of a control tube 68.

The grid 66 of control tube 68 is preferably connected to ground through a resistor 70 which may be shunted by a resistance 72 upon closure of a switch 74, thereby to change the amplitude of the signal wave which is impressed upon the grid 66. The cathode 76 of the tube 68 is connected to ground through a biasing resistor 78 which is shunted by a by-pass condenser 80. The screen 82 of the tube 68 may be connected to any suitable fixed potential, such as -100 volts, while the plate 84 is connected to the output circuit through a conductor 86.

The control tube 68 has a signal from the oscillator for the note No. 85 continuously impressed upon its grid 66, but the tube 68 is normally non-conducting because of the potential which is placed upon its suppressor grid 88. The suppressor grid is adapted to be connected to ground through an attack resistor R_{20} by a manually operable key switch 90, and is connected to an adjustable negative potential source 91 through a high value decay resistor R_{21} , while a condenser 92 connects the suppressor grid to ground.

Each of the gas tube oscillators 32 will supply a signal to its associated control tube 68, the signal from the gas tube oscillators being taken from a terminal 94 between the resistances R_{16} and R_{17} through a conductor 96. By closing switch 44, the shape of the wave impressed upon the grid of the control tube may be changed and hence the harmonic development of the note altered. Since the control tubes for the various oscillators are identical, only two such tubes are illustrated in the drawings, one associated with the oscillator for note No. 85 and the other

associated with the oscillator for note No. 73. However, the plates 84 of a plurality of the control tubes are shown in Fig. 2. In general, the plates 84 of control tubes 68 are connected in parallel groups of four each. Each group of plates 84 is connected to a common conductor 98 which is connected to one terminal of the primary winding 100 of an output transformer 102 either through one or more resistances 104 of different values or through a condenser 106, or through both these resistances and the condenser.

The other terminal of the primary winding 100 of the output transformer may be connected to a terminal 108 either directly, upon closure of a switch 110, or through any desired resonant circuit branch comprising inductances 112, 113 and condensers 114, 116 and 118. These condensers may be connected to shunt the inductance 112, and condensers 115, 117 and 119 may be connected to shunt the inductance 113. The condensers 114 to 119 may be selectively connected in the circuit by means of individually adjustable switch arms 120, 121 which are connected between the inductances 112 and 113.

The terminal 108 which is connected to the positive B supply, is also connected through a resistance 122 to the conductor 98, the resistance 122 being adapted to be by-passed by condenser 124 upon closure of a switch 126.

It will be understood that each group of plates 84 will have a circuit including resistances such as 104 and 122, and condensers, such as 106 and 124, whereas the network including the inductances 112 and 113, and condensers 114 to 119, may be common to the plate circuits of all of the control tubes 68, or, if desired, there may be two or more such networks, each network being common to a plurality of groups of plate circuits. For example, the instrument may be divided into two sections, the output for the higher pitch notes connected through one resonant circuit, while the output for the lower pitch notes is connected through another resonant circuit. In this way, the instrument may be adjusted to have two ranges of frequencies which will be accentuated. The output circuit is subject to considerable variation in design, to make possible the accentuation of certain frequencies and the attenuation of others. The various switches by means of which the groups of plate circuits are connected to the output circuits are preferably gang switches which may be simultaneously operated manually.

The secondary of the transformer 102 is connected through a preamplifier 128 to an amplifier 130, which supplies a speaker 132.

The above described relationship of the various oscillators and resonant output circuits is diagrammatically illustrated in Figure 3, wherein each oscillator is designated by a block marked 0 followed by the note number of the oscillator. Thus, the blocks marked 0-77 to 0-88 inclusive, represent the master oscillators for the notes Nos. 77 to 88 inclusive respectively, while the blocks marked 0-1 to 0-76 represent the gas tube relaxation oscillators for the notes 1 to 76 inclusive respectively. It will be noted that each oscillator representing block has an arrow leading to a smaller block representing the control tube 68 associated with the oscillator. These blocks are marked C-1 to C-88 inclusive, as designating the control tubes for notes Nos. 1 to 88 inclusive respectively. It will furthermore

be noted that oscillators for notes in octave relationship are in horizontal rows and connected by a series of arrows to indicate the fact that these oscillators are cascaded for frequency stabilization control.

Groups of the blocks representing the control tube, such as C-85 to C-88 inclusive, are connected by dash lines to a block marked RC-85-88. This latter block and the other similar blocks represent a resistive and capacitative network for each group of four notes. In Figure 2, the resistive and capacitative networks are illustrated by the resistances 104 and condensers 106.

It will be further noted that the resistive-capacitative networks are joined by a pair of dash lines, one group of which leads to a block marked LC-41-48 indicative of the inductive capacity mesh connected to receive the signals from the control tubes for the notes 41 to 48, and the other group of which leads to a block marked LC-1-40 indicative of the inductive capacity mesh connected to receive the signals from the control tubes for notes Nos. 1-40. These inductive-capacitative meshes are shown in Figure 2 as comprising the condensers 114 to 119, and inductances 112 and 113 and associated switches and circuits.

The signal from the blocks LC-41-48 and LC-1-40 are indicated as being supplied to a swell control, preamplifier, power amplifier, and loud speaker, in series.

In addition, Figure 3 shows that there is a vibrato apparatus for each pair of master oscillators. Thus, for example, the block V-78-88 is indicated as affecting the operation of oscillators 0-87 and 0-88. The blocks V-87-88, V-85-86, etc., each represent a vibrato apparatus such as shown in Figure 1, and including the vibrating reed 142 together with the means for maintaining it in oscillation, and the contacts 144 and 154 completing circuits to the tuning circuits of the oscillators.

It will be understood that the diagram of Figure 3 is not intended as a wiring diagram, but merely as illustrative of the functional relationship of the previously described parts.

Vibrato apparatus

As previously pointed out, the frequencies of the gas tube oscillators of a cascaded series are controlled by the master oscillator, so that if the frequency of oscillation of the master oscillator is varied at a vibrato periodicity, the frequencies of oscillation of the associated gas tube oscillators will be proportionately varied.

The means for periodically changing the frequency of oscillation of the master oscillators comprises a pair of condensers 134, 135 adapted to be connected in parallel with the condenser 16 by means of switches 136 and 137 respectively. These switches are also adapted to connect with the terminals of condensers 138, 140 which are adapted to be connected to ground through a vibrating reed 142 by means of a contact 144. The reed 142 carries a weight 146 of magnetic material which is adapted to be attracted by an electro-magnet 148 which is energized by a battery 150 whenever the reed swings upwardly to connect contact 152 with the ground. The electro-magnet 148 thus maintains the reed 142 in a state of continuous vibration. In the complete instrument, I preferably provide six independently vibrating reeds 142, the weights 146 thereon being so proportioned that the reeds will vi-

brate at slightly different frequencies. Each reed will thus be arranged to control the vibrato frequency shift of two oscillators. In the drawings, the contact 154 is a contact corresponding to the contact 144, but connected to a different oscillator.

By proper selection of the values of the condensers 134, 135, 138 and 140, the extent of change in frequency may be made such that the effect upon the listener is not one of actual change of pitch, but rather one of full, rich warmth of tone. The value of the condenser 134 with respect of that of condenser 138, and that of the condenser 135 with respect to that of condenser 140 are so chosen, that the frequency change introduced by the vibrato apparatus does not result in a change in the average frequency of the note. The switches 136, 137 may be independently operated so that three different degrees of vibrato may be obtained, i. e., (1) when switch 136 is connected to the condenser 134 and switch 137 is connected to the condenser 140, (2) when switch 136 is connected to condenser 138 and switch 137 is connected to condenser 135, and (3) when switch 136 is connected to condenser 138 and switch 137 is connected to condenser 140. When the switches are in the position that condensers 134 and 135 are in circuit, the frequency of oscillation of the oscillator will remain constant.

Since the frequency of oscillation of the master oscillator is determined not only by the condensers 16, 134, 135, 138 and 140 but also by the inductance of the coil 14, I utilize the inductance 14 as a convenient means for tuning the master oscillator, and the inductance 14 is therefore of a special construction in which the inductive reactance may be varied by small increments, preferably by varying the amount of iron effective in its magnetic circuit. It will be apparent that the complete instrument may be tuned merely by properly tuning the master oscillators. This is a very desirable feature since the tuning operation is thus so materially simplified that it may be done by the owner of the instrument and will not require the services of an expert tuner.

Operation of frequency generating system

The master oscillator is of well-known construction and except for the addition of the vibrato apparatus, will operate in the usual manner to generate oscillations of the desired frequencies. These oscillations are impressed upon the grid 30 of the gas tube 32 for the note 73 in the system illustrated, through the blocking condenser 22 and resistances 24 and 28. The condenser C₁₅ is being continuously charged through the resistances R₁₆ and R₁₇ until the potential across its terminals is sufficient to cause discharge of the tube 32. The discharge of the tube is, however, in part controlled by the potential upon the grid 30. Even though the condenser C₁₅ may not be charged to a sufficiently high potential by itself to cause discharge of the tube 32, the presence of a positive potential upon the grid 30 will, nevertheless, cause discharge of the tube 32 through the plate circuit. Thus, the tube will discharge only when a positive signal is impressed upon the grid 30, but discharge will not take place upon each positive swing of the grid of the tube because the values of the resistances R₁₆ and R₁₇ with respect to the capacity of the condenser C₁₅ is such that upon alternate positive swings of the grid 30, the potential of the charge on the condenser will be

insufficient to cause discharge of the tube even though such discharge would be assisted by the positive potential upon the grid.

I am of course aware that gas filled triodes have been used for relaxation oscillators in various circuits where the frequency of relaxation is controlled by a signal applied to the grid of the triode. This is common practice in sweep circuits for cathode ray oscillographs. In all such circuits with which I am familiar, a relatively fixed grid bias between grid and cathode is provided with means for critically adjusting this bias so that a small signal applied to the grid will be just sufficient to cause discharge through the tube under certain circumstances. In all such circuits, the exact tube characteristics play an important role inasmuch as a definite grid voltage is necessary for each particular value of cathode to plate potential.

I have found in practice that there is a considerable variation between different tubes of the same lot, and serious variations which occur for the same tube due to aging, temperature and emission. These differences in tube characteristics make such circuits undesirable for an instrument of this type. I have found that the circuit disclosed herein makes unimportant the exact characteristics of the tube itself, so that the factors controlling the frequencies at which the tubes will operate can be the constants of the circuit, particularly the resistance R₁₆ and the condenser C₁₅. This is due to the fact that an enormous signal develops between cathode and ground across the resistances R₁₆ and R₁₇, and that this signal develops between grid and cathode because the grid is tied back to ground through a resistor 50. The secondary of the transformer 46 would remain at substantially ground potential except for the tripping signal delivered by the transformer 40.

As soon as the tube ionizes, a large current flows from plate to cathode through the condenser C₁₅, the primary 38 of the transformer 40, and the resistance 36. Owing to the inductance of the transformer 40, the condenser C₁₅ is not only discharged, but will receive a charge of opposite polarity so that when the heavy current flow stops, the cathode will be left at a potential more positive than the plate. At this instant, the potential of the cathode with respect to ground will be the full potential of the B supply system plus the potential developed across the condenser C₁₅, and the grid will be left at a potential which is more negative than the cathode by this amount. Thereafter the condenser C₁₅ starts to discharge through the resistance R₁₆ and later begins to charge to the opposite polarity.

When the next signal impulse from the oscillator one octave higher arrives, the charge on the condenser C₁₅ will be very small so that the voltage between cathode and plate will be correspondingly small. The bias of grid to cathode will be as large as the voltage of the B battery at the time when the charge across the condenser C₁₅ is zero. It therefore follows that the signal supplied to the grid from the oscillator one octave up can be made very large without causing ionization of the tube for this impulse. When the next impulse comes, the condenser C₁₅ will be charged so that the potential between cathode and plate will be large and the signal delivered to the grid from the tube one octave up will not only be sufficient to cause ionization, but would actually drive the potential of the

grid positive with respect to the cathode if the tube required such a signal to cause it to ionize. Thus, the very large voltage swings which can be impressed on the grid make the differences in characteristics of different tubes inconsequential by comparison with these high voltages.

Thus, by proper choice of values for the condensers, resistors and transformer inductances, each tube will supply the correct frequency regardless of wide variations in tube characteristics. In earlier experimental circuits, changes in tube characteristics occasionally caused tubes to ionize at each impulse of grid signal, or to ionize for each third impulse. In that case, the note will of course suddenly play one octave up or down by the musical interval known as the fifth. With the circuit described above, all tubes of the same general type, as long as they function at all, play correctly without change in resistors or condensers and over wide variations in supply voltage, etc.

Another advantage of this circuit lies in the ability of each tube circuit to supply an independent signal with complete absence of frequencies associated with the corresponding tube one octave lower. Earlier attempts to produce a musical instrument in which independent signals were produced by frequency division were always unsuccessful, as far as I am aware, owing to the presence of undesired lower frequencies which are exceedingly troublesome for reasons which I will now describe.

The distorter and control tube 68, Fig. 2, has a signal impressed upon its grid 66 which is derived from the voltage which develops across the resistor R₁₇, Fig. 1. This resistor R₁₇, which may have a value such as 10,000 ohms is in series with the resistance R₁₆, which may be, for instance, 300,000 ohms. The resistor R₁₇ is shunted by the condenser C₁₄ and if this condenser C₁₄ is omitted, the shape of the wave of voltage across R₁₇ is that of a saw-tooth. Such a wave may be analyzed into a fundamental and a series of harmonics both of even and odd terms. The operation of the control tube, which is described in detail in my application Serial No. 199,613, filed April 2, 1938, now Patent 2,126,464, granted August 9, 1938, is such that only the most positive excursions of grid voltage are effective to produce a plate current which flows in impulses in order to produce a tone very rich in harmonics.

If the signal which develops across the resistor R₁₇ contains even very small amounts of frequencies lower than the fundamental frequency associated with that note, or if it contains any odd harmonics of a lower frequency such as odd harmonics of the fundamental of the octave down, then sum and difference terms will arise in this non-linear circuit which will completely spoil the musical effect of the note. Now the gas filled tube 32 associated with note No. 73, in addition to supplying a signal for that note, must operate to trip the gas tube one octave down associated with note No. 61. When this second tube ionizes, there is an opportunity for a signal of lower frequency to be reflected back into the tube of note No. 73 through capacity effects within the tube of note No. 61, the plate of which exhibits violent voltage changes at a frequency an octave lower. It is therefore necessary to prevent reflections from this source from entering the signal supplied by the tube of note No. 73. This is done by means of the circuit shown and the proper choice of the constants

of the circuit. Thus, a resistance 50, Fig. 2, which may have a value of 250,000 ohms is inserted in series with the grid connection to the driven tube so as to limit to a small value the current which may flow in this circuit upon ionization of the tube. The signal to drive the tube 32 for note 61 is derived from the secondary of transformer 40, Fig. 1, this secondary 46 having preferably many less turns than the primary 38 so as to reflect the smallest possible load into the driving circuit including the primary 38, the resistance 36, the plate-to-cathode circuit through the tube, and the condenser C₁₅. The resistance 36 may have a value of 2,000 ohms. It will be noted that the signal for note No. 73 is not taken from this circuit, so as to further avoid the possibility of feed-back. The condenser C₁₅ is charged at a relatively slow rate through the resistances R₁₆ and R₁₇ from the "B" voltage supply. When ionization takes place in the tube, the condenser discharges at an exceedingly rapid rate through the cathode plate circuit just described, which is of very low impedance. The only feed-back from the lower note which could occur is during the exceedingly short period of time of discharge. Thereafter the plate circuit ceases to have any effect on the condenser C₁₅ which again starts to charge through the resistances R₁₆ and R₁₇. By this arrangement the effect of the driven tube is prevented from causing reflection into the driver, and the use of additional intermediary tubes for preventing reflection is avoided.

The resistance 36 and inductance 38 cause the wave of voltage between the cathode 42 and ground to assume the form of a saw-tooth wave having slightly rounded peaks. The signal from the gas tube oscillator for the note 73 is derived from the terminal 94 and is likewise of generally saw-tooth wave form, and is impressed upon the grid of the associated control tube 68 through conductor 96. The negative potential impressed upon the suppressor grid 88 through the resistance R₂₁ is normally sufficient to prevent any plate current in the tube 68. When, however, it is desired to sound the note 73, the key switch 90 associated therewith is depressed, thus connecting the suppressor grid 88 to ground through a resistor R₂₀.

Upon initial closure of this switch 90, the condenser 92 is discharged through the resistor R₂₀ and the potential upon the suppressor grid 88 will therefore be changed to ground potential gradually instead of instantaneously. This is a desirable feature since the corresponding gradual increase in plate current will cause the note to be sounded with a gradual attack instead of with a sudden abrupt attack. Since the resistor R₂₀ is of much lower value than resistor R₂₁, the suppressor grid will shortly attain ground potential, with a resultant flow of plate current.

Upon release of the key, the potential of the suppressor grid will not immediately return to its normal negative potential but, due to the discharged condition of the condenser 92 at this time and the relatively high resistance of the resistor R₂₁, the drop in potential of the suppressor grid will be gradual at a logarithmic rate. The resultant gradual decay in the plate current and consequent decay in the note being sounded is very advantageous since it provides the effect of reverberation in the music being rendered. The instrument may thus be played in a room which is acoustically relatively "dead" without disadvantage.

The form of the saw-tooth wave impressed upon the grid of the control tube 68 may be altered to have its positive peak made more rounded by closing the switch 44 and thus connecting the condenser C₁₈ in parallel with the condenser C₁₄. The wave thus impressed upon the grid of the control tube may thereby be controlled so as to have different degrees of harmonic development, it being understood that the wave having the sharper peaks will cause distribution of the greater proportion of its energy in the higher harmonics with a resultant brilliancy or keenness in the sound produced. These effects are more fully described in my application Serial No. 199,614, filed April 2, 1938, now Patent 2,126,682, granted August 9, 1938.

By means of the various gang switches associated with the resistors 104 and condenser 106, as well as the network including the inductive impedances 112 and 113 and condensers 114 to 119, and associated switches 120, 121, 110 and 126, the frequency of resonance may be varied, and the quality of tone of the instrument as a whole may be varied.

The system may be provided with a volume control diagrammatically illustrated in Fig. 2, comprising a variable resistance 152 and condenser 154 connected across the secondary winding of transformer 102.

The provision of the vibrato apparatus and the adjustable resonance output circuits makes it possible to produce music of pronounced string-like quality simulating that produced by instruments of the violin family, with the pronounced advantage that one musician can, by means of the instrument, simulate the effects produced by a string quartet, or the like, since of course the musician can play the several parts with the instrument of the present invention because it will be provided with a keyboard similar to that of the standard piano or organ.

While I have shown and described a particular embodiment of my invention, it will be apparent to those skilled in the art that various changes and modifications may be made without departing from the essential features of the invention. For example, the master oscillators may be replaced by any other suitable group of generators of electrical impulses; different types of output and key controlled circuits may be provided for transmitting the electrical impulses of the generators to the electro-acoustic translating means; and various forms of frequency controlled oscillators or frequency dividing circuits may be utilized in various combinations. I therefore desire to include within the scope of my invention, as defined by the following claims, all such similar constructions whereby substantially the same results may be obtained by substantially the same or equivalent means.

I claim:

1. In an electrical musical instrument, the combination of a plurality of master oscillators each having a tuned reactance mesh controlling its frequency of oscillation, a plurality of means for periodically changing the reactances of the meshes of a plurality of said oscillators at slightly different vibrato frequency rates, and a plurality of cascaded series of generators, each series having its frequencies controlled by one of said master oscillators, whereby changes in frequency of oscillation of said master oscillators will cause proportionate changes in frequencies of their associated series of cascaded oscillator.

2. In an electrical musical instrument, the

combination of a source of electrical impulses of accurately maintained musical frequency, a relaxation oscillator for producing impulses of one half the frequency of said source, said relaxation oscillator comprising a gas filled multi-electrode thermionic tube having a cathode, grid and plate; a circuit connecting the grid of said tube with said source, a cathode-plate circuit including a source of direct current potential having its positive terminal connected to the plate of said tube through an inductance and a resistance element, and having its negative terminal connected to said cathode through a relatively high value resistor; a condenser connected between said cathode and the positive terminal of said direct current potential source, and means connected across said resistor for deriving a signal from said oscillator.

3. In an electrical musical instrument, the combination of a source of electrical impulses of fundamental frequency of a note of the musical scale, electro-acoustic translating means, and means for controlling the transmission of the signal generated by said source to said translating means, said control means comprising an electron discharge device having a cathode, plate and at least two grids, a circuit for impressing a signal from said source upon one of said grids, a direct current potential source connected to the second of said grids normally to prevent said tube from transmitting said signal, and key controlled switch means for changing the potential on said second grid in a manner to render said tube capable of transmitting said signal.

4. In an electrical musical instrument, the combination of a source of electrical impulses of accurately maintained musical frequency, and a relaxation oscillator for producing impulses of exactly one half the frequency thus produced by said source, said relaxation oscillator comprising a gas filled multi-electrode thermionic tube having a cathode, grid and plate; means for impressing impulses from said source upon the grid of said tube; a cathode-plate circuit including an inductance, a source of direct current potential and a high resistance in series; and a condenser connected between the cathode of said tube and a positive terminal of said direct current potential source, said condenser being charged from said source through said high resistance and discharged through said cathode plate circuit of said tube.

5. In an electrical musical instrument, the combination of a plurality of sources of electrical impulses of frequencies of the musical scale, a pentode control tube for each of said sources and having its control grid connected to receive impulses from its associated source, an output circuit connected in the plate circuit of said control tube, and key controlled means for changing the potential on the suppressor grid of said control tube thereby to render said tube capable of transmitting to said output circuit the signal impressed upon its grid.

6. A relaxation oscillator for generating a signal having a frequency of a note of the musical scale comprising, a gas filled tube having an anode, a cathode, and a grid; a source of plate current; an input circuit for said tube having means for impressing impulses of twice the frequency of said note upon the grid of said tube; a high resistance and an inductance connected in series with said source between said cathode and said plate; and a condenser connected between

the positive terminal of said source and said cathode.

7. The combination set forth in claim 6 in which said high resistance is connected between the negative terminal of said source and said cathode.

8. In an electrical musical instrument having a plurality of groups of generators, each generator producing electrical impulses of one of the notes of the musical scale, the combination of, a plurality of vibrato frequency devices, and means for connecting each of said devices to a group of said generators for varying the frequencies thereof, whereby the vibrato on different notes may be made to differ in phase and frequency.

9. The combination set forth in claim 8 in which each of said vibrato devices comprises a vibratory element determining its frequency, and means for maintaining said element in vibration.

10. In an electrical musical instrument having a master oscillator, means for varying the frequency of oscillation thereof to produce a vibrato effect, comprising a tuning element for said oscillator, a member capable of vibration at a vibrato frequency rate, electro-magnetic means for vibrating said member, and a switch operated by said member to render said tuning element alternately effective and ineffective, thereby to change the frequency of oscillation of said oscillator.

11. In an electrical musical instrument having a master oscillator for controlling the frequency of oscillation of a plurality of cascaded generators, means for introducing a vibrato change in frequency in the impulses produced by said master oscillator and its controlled generators comprising, a reactance mesh determining the frequency of oscillation of said master oscillator, a member moving at a vibrato frequency rate, a circuit including means for changing the reactance of said reactance mesh, and a switch operated by said member to open and close said circuit at a vibrato frequency rate.

12. In an electrical musical instrument having twelve cascaded series of generators, each generating the fundamental frequency of a different

note of the musical scale and each series generating frequencies of notes in octave relationship, and having twelve tunable master oscillators, one for each series of cascaded generators, the combination of a plurality of members moving at slightly different vibrato frequency rates, a plurality of switches operated by said members, and means including said switches for changing the tuning of the master oscillators.

13. In an electrical musical instrument having a master oscillator and means for varying the frequency of oscillation thereof to produce a vibrato effect, said means comprising a tunable element for said oscillator, the combination of a member moved continuously at a vibrato frequency rate, and means operated by said member to render such tuning element alternately effective and ineffective thereby to change the frequency of oscillation of said oscillator at said vibrato frequency rate.

14. In an electrical musical instrument having a master oscillator for controlling the frequency of oscillation of a plurality of cascaded generators, means for introducing a vibrato change in frequency in the impulses produced by said master oscillator comprising a reactance mesh including a capacitance determining the frequency of oscillation of said master oscillator, a member moving at a vibrato frequency rate, a circuit including said capacitance for changing the reactance of said reactance mesh, and a switch operated by said member to open and close said circuit at said vibrato frequency rate.

15. In an electrical musical instrument having a plurality of cascaded series of generators, each generating impulses of a frequency of a different note of the musical scale and each series generating frequencies of notes in octave relationship and having a plurality of master oscillators, one for each of said series of cascaded generators, the combination of a plurality of members moving at slightly different vibrato frequency rates, a plurality of switches operated by said members, and means controlled by each of said switches for changing the tuning of one of the master oscillators.

LAURENS HAMMOND.