May 11, 1943. R. C. FISHER 2,318,936

MULTIFREQUENCY OSCILLATOR

Filed April 7, 1941 4 Sheets-Sheet 1

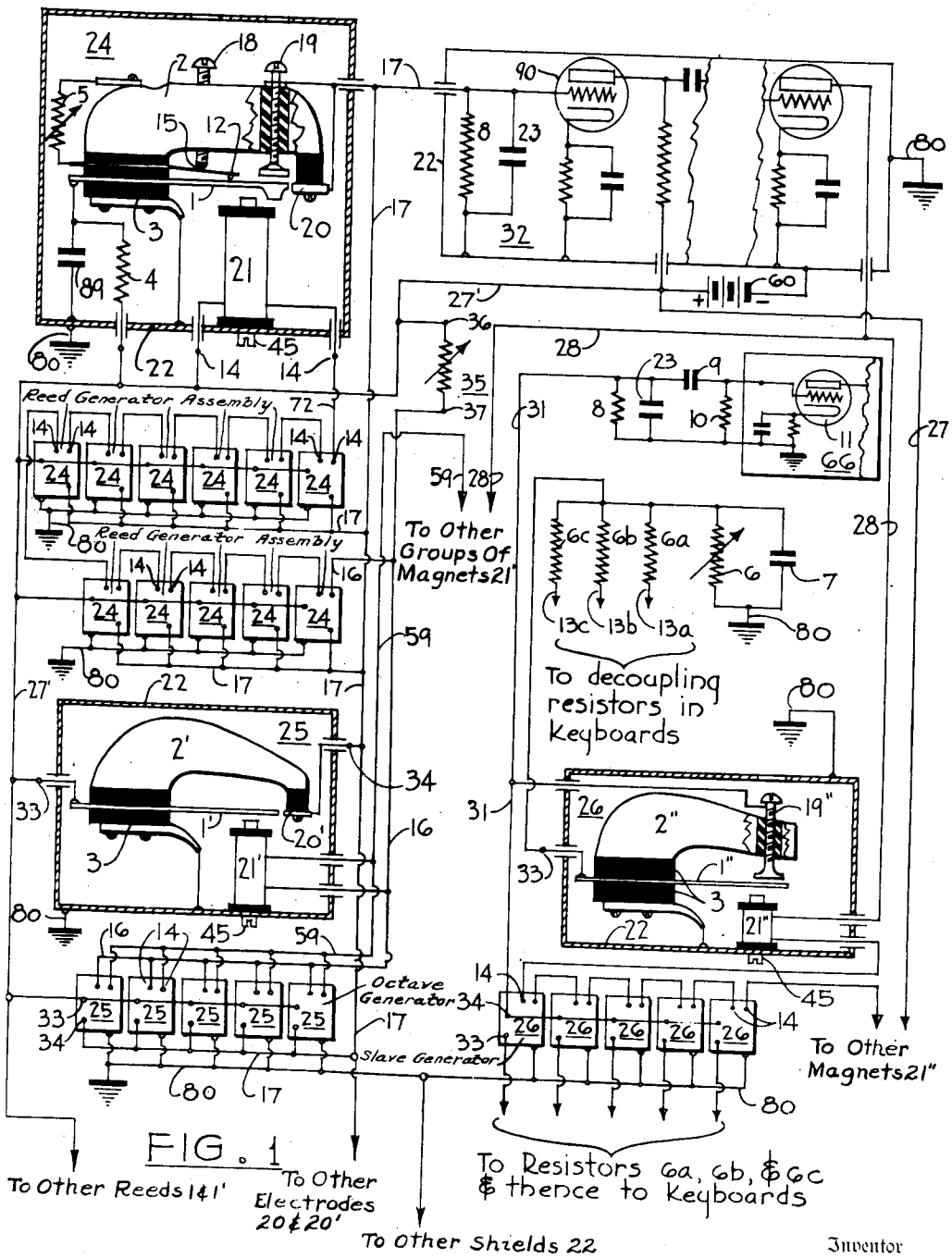


FIG. 1

Inventor

Raymond C Fisher

Attorney

May 11, 1943. R. C. FISHER 2,318,936

MULTIFREQUENCY OSCILLATOR

Filed April 7, 1941 4 Sheets-Sheet 2

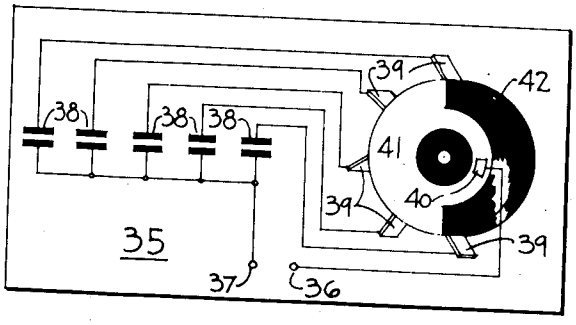


FIG. 2

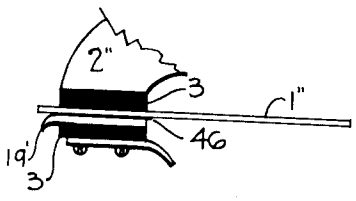


FIG. 4

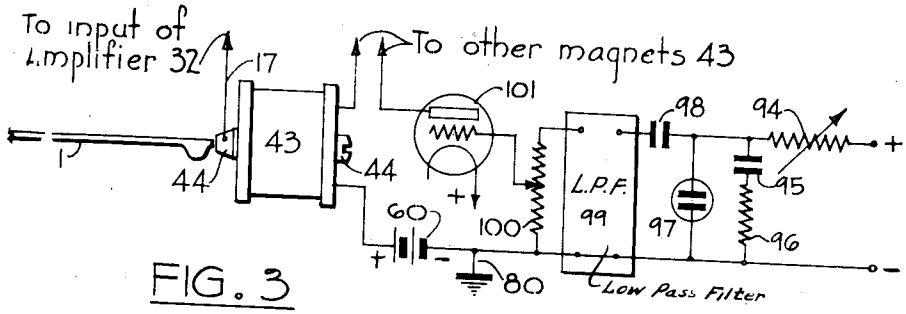


FIG. 3

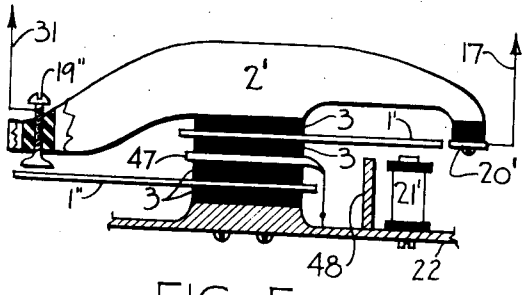


FIG. 5

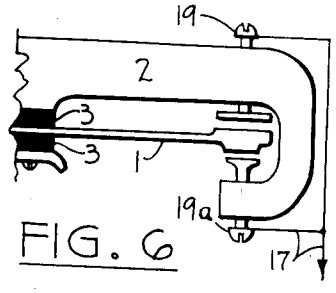


FIG. 6

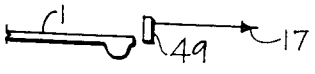


FIG. 8

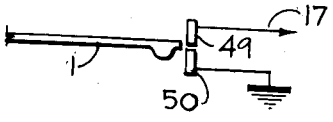


FIG. 7

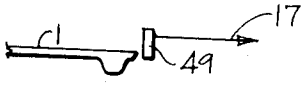


FIG. 9

Inventor

Raymond C. Fisher

Attorney

May 11, 1943. R. C. FISHER 2,318,936

MULTIFREQUENCY OSCILLATOR

Filed April 7, 1941 4 Sheets-Sheet 3

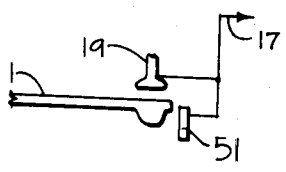


FIG. 10

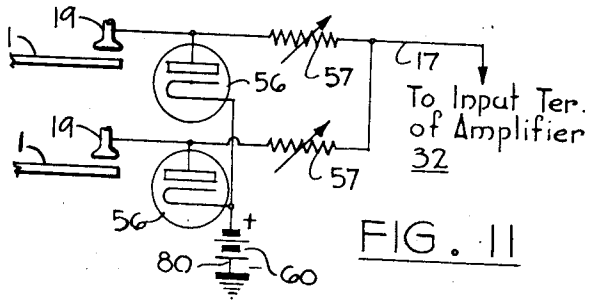


FIG. 11

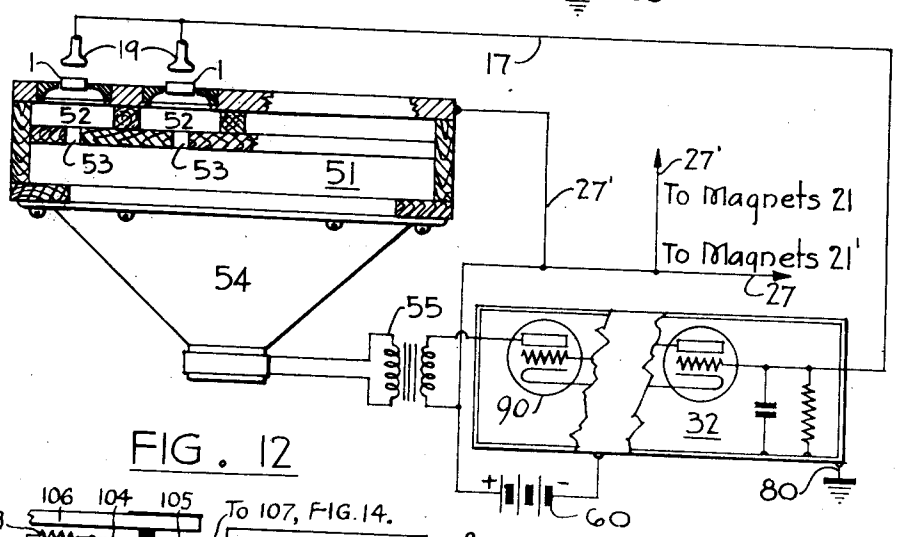
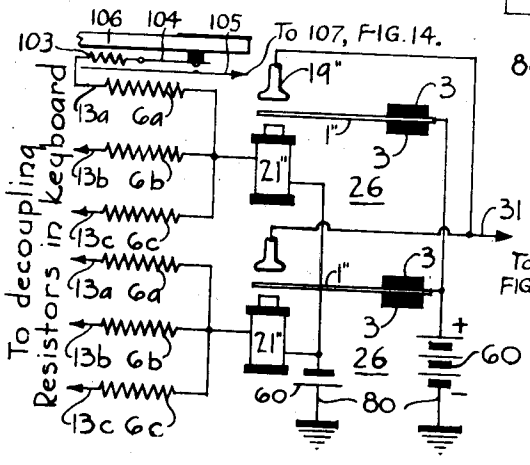


FIG. 12



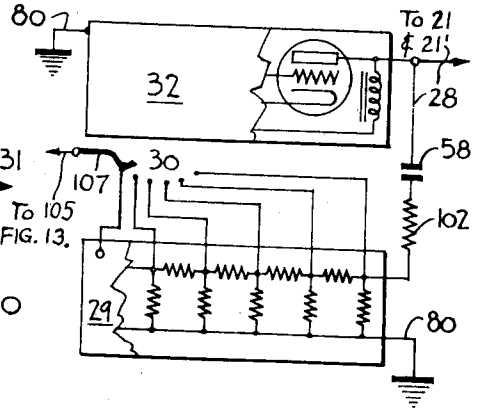


FIG. 13

FIG. 14

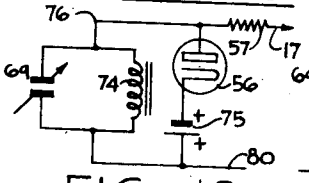


FIG. 16

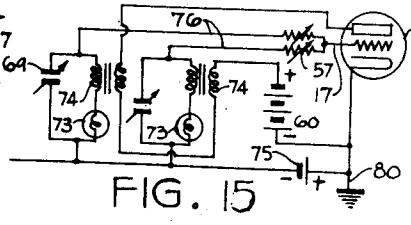


FIG. 15

Inventor
Raymond C. Fisher

May 11, 1943. R. C. FISHER 2,318,936

MULTIFREQUENCY OSCILLATOR

Filed April 7, 1941 4 Sheets-Sheet 4

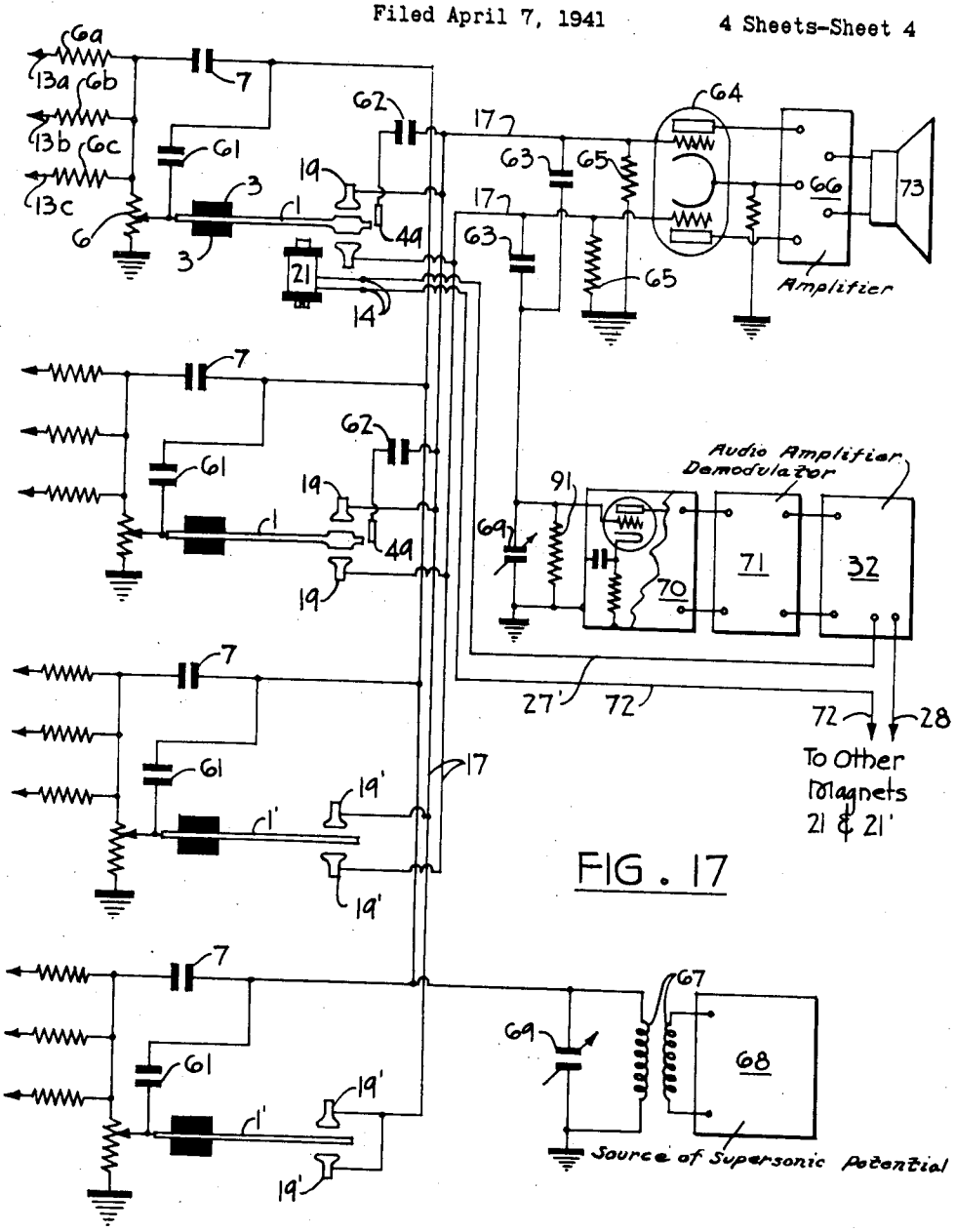


FIG. 17

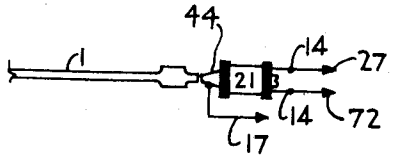


FIG. 18

Inventor
Raymond C. Fisher

Attorney

Patented May 11, 1943 2,318,936

UNITED STATES PATENT OFFICE

2,318,936

MULTIFREQUENCY OSCILLATOR

Raymond C. Fisher, Tacoma, Wash.

Application April 7, 1941, Serial No. 387,270

20 Claims. (Cl. 250—36)

My invention relates to the art of generating periodic electric currents by means of resonant or oscillatory electrical or mechanical means in combination with an amplifying electron tube system adapted to maintain continuous oscillation in such means.

It has particular application to the art of generating periodic currents suited to the production of musical tones.

One object of my invention is to provide generating means of the class set forth above, adapted to produce a number of different frequencies simultaneously without a correspondingly large number of electron tube amplifiers.

Another object is to provide a type of multifrequency generator or oscillator having amplitude and frequency stability sufficient for musical applications without undue maintenance difficulties or complication in the apparatus.

A further object is to provide an individual means for limiting the amplitude of oscillation of a plurality of resonant or oscillatory electrical or mechanical elements, all of which plurality are maintained in continuous oscillation by means of a common amplifier, without at the same time introducing mutual interference between the several resonant elements.

Another object is to provide novel means for varying or modulating at a subaudible periodic rate the frequency produced by such resonant means for the purpose of vibrato effects.

Another object is to utilize the resonant properties of a sharply tuned element to effect an organ-like attack and decay of tones.

Another object is to provide a coupling means through which a mechanically tuned or resonant element may drive or actuate another tuned element in a source of potential, the second element being resonant to the same frequency as the first or to a multiple thereof.

Still another object is to prevent leakage of electric current between the mutually vibratile electrodes of a potential-generating condenser.

Other and further objects will appear from the following description and the accompanying drawings, among which:

Figure 1 is an assembly of vibratile or oscillatory reeds, adapted for use in a musical instrument, together with means for maintaining the same in vibration and means for limiting the amplitudes of vibration of the individual reeds.

Figures 2 and 3 show means for producing vibrato effects in connection with the reeds of Figure 1.

Figure 4 shows details of an electrostatic means for picking up the vibrations of a reed.

Figure 5 shows vibratile reeds together with means for mechanically coupling the two together.

Figures 6 to 10 inclusive show forms of electrostatic pickup from a reed which are adapted to limit the amplitude of oscillation of said reed.

Figure 11 shows a purely electrical means for accomplishing the same general result as Figures 6 to 10.

Figure 12 shows an acoustic means for accomplishing the same general result.

Figures 13 and 14 show an electrical network adapted to actuate a group of secondary reeds from a set of primary tone generators.

Figures 15 and 16 show resonant circuits maintained in continuous oscillation by means of an amplifier, together with means for limiting the amplitude of oscillation of each of said circuits.

Figure 17 shows a supersonic-frequency network whereby a plurality of mechanically resonant members may be simultaneously kept in continuous oscillation and limited as to amplitude.

Figure 18 shows details of magnetic means adapted, in conjunction with parts of other figures, to limit the amplitude of oscillation of a mechanically resonant member.

Suppose it is desired to generate a large number of frequencies simultaneously, such as the ninety-six one might require for eight octaves of a musical instrument. Naturally, the means for accomplishing this should be as simple as possible. To this end, I should prefer to make a single amplifier serve in common for all of them, or at least for as large a part of them as may be. In the usual single-frequency oscillator, the one or more tubes of the amplifier itself function to limit the amplitude, by virtue of its grid being driven positive. See "Resistance Stabilized Oscillators," by F. E. Terman, Electronics, July 1933, published by McGraw-Hill Publishing Co., Inc., New York, N. Y. In the multi-frequency oscillator, however, the common amplifier cannot in general do this successfully. Its grid circuits are subjected to a large number of different frequencies, each associated with a different one of the multiplicity of oscillatory circuits, and if a potential component at one of these frequencies drives the amplitude-limiting grid positive, then potentials at all the frequencies will be limited simultaneously. The result is generally that some components, perhaps all but one, are so suppressed by the automatic limiting action, that

only one of them, or at best only a few actually appear. Moreover, the non-linearity present in the amplifier results in a large number of sum and difference frequencies, which tend toward frequency instability and interlocking of the various frequencies. For critical applications, such as a musical instrument, this state of affairs is nautrally to be avoided.

It will be evident that a common amplifier for all of the multiplicity of oscillatory circuits and frequencies is usable only provided it is sufficiently free from non-linearity, and provided one provides a separate automatic amplitude limiter associated with each such frequency and oscillatory circuit, and so arranged that it has no appreciable influence on the amplitude or frequency associated with any of the other oscillatory circuits. Each limiter must be responsive solely to currents or potentials of its associated frequency, and it must be capable of limiting its associated current or voltage to a magnitude low enough so that the amplifier will not be overloaded by the sum total of all the potentials which it must amplify. Amplitude limitation must be accomplished otherwise than by the positive potentials in a grid circuit common to the several frequencies. Otherwise, the amplifier cannot be substantially linear, as above postulated.

In case a common amplifier is to be thus employed, one should, to express the matter in general terms, provide a separate feedback channel for each such frequency, each of these channels having a resonant frequency-determining means (in the above case the oscillatory circuit) and also an amplitude-limiting means individual to it and to its associated frequency. Where the number of frequencies to be generated is great, I can in general afford to build a fairly elaborate amplifier, since it may serve for all the frequencies. On the other hand, since the frequency-determining means and the amplitude-limiting means must be duplicated for each frequency desired, I should prefer to keep these as simple as possible, even though to do so might necessitate a somewhat more elaborate amplifier.

The above discussion has been carried out with reference to an oscillatory circuit for the determination of each frequency. However, it is well known in the art that various other sharply resonant or sharply tuned frequency-determining agencies may be used, such as metal bars, bells, strings, reeds, tuning forks, or other such mechanically resonant elements. In addition, piezo-electric or magneto-strictive elements may be similarly used with suitable amplitude-limiting means. Any of these elements may be maintained in continuous oscillation or vibration by means of an electron tube amplifying system, as known in the art. My invention comprises all such suitable electro-mechanical or purely electrical means for determining the frequency.

Because of its unusual simplicity, purity of wave form, and stability of generated frequency, however, I prefer to use as the resonant element an oscillatory ferromagnetic reed, illustrated at 1 in Figure 1, which forms a part of a reed generator assembly 24. The remainder of the figure is one particularly well suited for use in an electronic musical instrument, but it will be apparent that it may have other applications as well.

The reed is suitably supported by a rather massive casting 2, being electrically insulated therefrom by means of insulating Bakelite washers 3, and by means of Bakelite or hard rubber sleeves around the mounting screws. These sleeves are not illustrated, being similar to those commonly used with relay springs and key contacts in the communication art. The reed is held at all times at a suitable potential with respect to ground by a source of direct polarizing potential 60, being connected thereto via conductor 27' and resistor 4.

At 19, I show an adjustable electrode, supported by casting 2 and insulated therefrom, as shown. The electrode has a disk-shaped lower extremity, providing an appreciable electrostatic capacitance with respect to the reed. The electrode and reed thus constitute two electrodes of a variable condenser or capacitor, whose capacitance periodically increases and decreases as the reed oscillates. In consequence of this variation, and of the polarization provided by the source 60, an alternating potential at the frequency of the reed vibration will appear at the input terminals of amplifying electron tube system 32. This amplifier may have as many stages of amplification as are needed to enable it to perform its function, as will appear. The amplifier being suitably linear, as above postulated, the same frequency and substantially the same wave form will appear at the output terminals of the amplifier. A circuit connection is provided from the plate-connected output terminal via conductor 28', through certain magnets not illustrated, via conductor 59, through elements 25 (to be later explained), via conductor 16, resistor 35, through eleven of the elements 24 to a terminal 14 of electromagnet 21. From the magnet, the current returns via conductor 27' to the B-battery 60. In short, the magnet 21 is in the plate circuit of the output tube of the amplifying electron tube system 32. Inasmuch as the magnetic path of the magnet is chiefly in air, its flux will be substantially proportional to the current traversing its winding. Since the pulsations of flux originate at the reed, they will have the same fundamental frequency as that of the reed. Hence the reed, being tuned to this frequency, may respond strongly.

Mathematical calculation will show that, by proper control or choice of the condenser 23, grid leak 8, variable impedance 35 which is shunted across the several elements 24, and of other coupling impedances of the amplifier, not shown, the magnetic force impressed on the reed may be made to be 180 degrees out of phase with the velocity of the reed; in other words, with the force impressed by the mechanical resistance of the reed. The elements 23 and 8 should also be chosen so as to render the amplifier input network quasi-linear, as explained in my Patent No. 2,055,719.

Now, mechanical resistance is analogous to electrical resistance, and the reed vibration may be caused to build up in amplitude by making the fundamental component of force contributed by the magnet somewhat greater than that dissipated or expended in the mechanical resistance.

Some way must, however, be provided to limit the amplitude of vibration to some chosen value, as discussed hereinabove with respect to the oscillatory circuit. This function is performed in Figure 1 by contact spring 12 and contact adjusting screw 18, insulated from the contact by its insulating tip 15. As soon as the reed attains a certain amplitude of oscillation determined by the setting of screw 18, the reed makes periodic contact to the spring at each upward swing. During each period of contact, the reed is partially grounded through resistor 5, casting 2, the two screws at the lower left-hand part of

the casting, the electrostatic shield **22**, and the ground connection **80**.

As has been previously pointed out, the reed is maintained at a potential above that of ground by virtue of its connection to a source of polarizing potential **60**. There is a condenser **89**, connected between the reed and ground. Because of this, the reed potential cannot be altered instantaneously. By virtue of the voltage-dividing action of the resistors **4** and **5**, however, the average potential over a cycle will be less the greater the amplitude of reed vibration, because for large amplitudes the contacts at **12** are made for a greater fraction of a cycle than for small amplitudes. By proper choice of the electrical magnitudes of resistors **4** and **5** and condenser **89**, the time constant of the network wherein they appear can be made considerably greater than one period of the reed vibration, and the polarizing potential of the reed will remain sensibly constant throughout a cycle.

The alternating potential impressed upon the input terminals of amplifier **32** is directly proportional to the polarizing potential. Thus, lowering the polarizing potential effects a decrease in what I here term the electron tube system input transduction factor; that is, it lowers the ratio between the amplitude of fundamental component of amplifier input potential and the fundamental component of reed velocity. It is clear, then, that the reed will attain an amplitude just sufficient to permit the amplifier to exactly overcome the reed's mechanical losses, and that it will hold this amplitude until some change occurs in the mechanical or electrical conditions, such as a change in amplifier B potential or the like. In the latter case, the reed amplitude may change slightly to accommodate itself to the new conditions. It will be seen, however, that the amplitude may be made very stable indeed by proper adjustment of variable resistor **5**, adjusting screw **18**, magnet core **45**, and the usual attention to the supply potentials, etc.

The magnet core is threaded inside an insulating sleeve, not shown, which insulates it from the winding in the usual fashion, and has a slotted head, as illustrated, to facilitate accurate adjustment.

In order that the reed itself shall be the determining factor as regards frequency, the contact spring **12** should be made very light in weight and its force against the reed should be negligible as compared with the stiffness forces of the reed itself. If these conditions are fulfilled, if the amplifier is linear, and if the amplitude of the reed is sufficiently small as compared with the minimum distance from it to the top of magnet **21**, and from the electrode **19**, then the reed's motion will be nearly enough sinusoidal for all practical purposes, and the output potential of the amplifier **32** will likewise be so.

With certain amplifiers, it will be seen that the electrode **19** should be beneath the reed instead of above it, in order to provide regenerative feedback. In such case, the electrode might be conveniently mounted on the upper end of the core of magnet **21**, or be made integral therewith. To prevent electrostatic coupling between the magnet winding and the core and electrode, electrostatic shielding isolating the winding from the core and electrode would be advisable. This could be similar to the split shielding commonly used between windings of transformers in the radio art. A similar shield might also be used if necessary between winding and core in the magnets of Figures 3 and 18, as will appear. The shield in every such case should be grounded.

The contact spring **12** need carry only a small current at any time; scarcely enough, in fact, to produce visible sparking, provided a small enough condenser is used at **89**. The destruction of the contact point will be very much less than though it directly controlled the current in the magnet **21**, as in the conventional contact-controlled tuning fork. Moreover, the wave form of current where contacts are used would be too far from sinusoidal for use in the present environment. If desired, one contact point may be placed in the reed at the point where the adjustable contact **12** touches it, and both may be of platinum-iridium or other noble metal to avoid contact corrosion or oxidation. The inserted contact point does not appear in Figure 1, since it may be flush with the top of reed **1**. However, there may be considered to be two contact points, one on the reed and one on the spring, although one of these may be an integral or non-integral part of the reed proper.

If the amplifier impresses upon an oscillatory circuit any potential component in quadrature with the current in that circuit, and if the circuit is rendered self-oscillatory by the amplifier, then the presence of the quadrature component will produce a change in the frequency generated. A similar phenomenon will occur in the case of the reed or other mechanically oscillatory element. In accordance with the principles enunciated in Chapter IV, of "Elements of Acoustical Engineering," by Harry F. Olson, published by D. Van Nostrand Co., Inc., 250 4th Ave., New York city, reed velocity is analogous to current in the oscillatory circuit, and a force impressed on the reed which is in quadrature with the velocity of the reed will thus have the effect of altering the frequency of the reed. By a variation of the impedance of the element **35**, the phase relationship between amplifier input potential and potential drop across the magnet **21** may be varied. The impedance **35** may be a resistance, a capacitance, an inductance, or any combination of these which may be suitably varied. It is clear that, if it be varied periodically at a subaudible frequency of from, say, five to ten cycles per second, and if the variation in reed frequency and pitch varies accordingly, the result so far as the ear is concerned will be similar to that of the vibrato of a musical instrument. A suitable construction for this impedance will be suggested hereinafter.

It has now been shown how a single mechanically oscillatory or resonant reed, together with an amplifier and other associated equipment, may be made to continuously generate a sinusoidal current or voltage of constant amplitude. I now propose to show how other reeds and associated equipment, maintained in continuous oscillation by the same amplifier, may be employed to simultaneously generate other frequencies, without mutual interference. The reed **1** above discussed was a part of a reed generator assembly **24**, and constituted a part of a channel adapted to feed back potential from the output terminals of the amplifier to the input terminals thereof. We may assume that this reed is so constructed that its assembly maintains a frequency of 32.7 cycles per second, which is the frequency of 16-foot C. In order to give the reed a sufficiently low pitch, it is constructed with a rather massive tip, as shown. I may wish also to generate the other eleven semitones of the 16-foot octave, from C#

to B inclusive. To this end, I provide eleven other assemblies 24, each in an individual channel between the output and the input terminals of the electron tube system. These other eleven are shown merely as boxes, although it is to be understood that they are exactly like the assembly 24 shown at the upper left-hand corner, except in such respects as may be required to enable each to produce and to continuously maintain its associated single fundamental frequency. For example, in general the higher the pitch, the shorter and lighter is the reed for its generation.

It will be observed that each of the assemblies has its individual amplitude-limiting means in the form of a contact spring 12 and associated parts. The twelve magnets 21 are connected in series as shown. I wish to make it especially clear that each of the amplitude-limiting means is adapted and electrically connected to control and limit the amplitude of oscillation of its associated reed and of the potentials and currents associated therewith, but not the amplitudes associated with any reed among the other eleven present. I also wish to point out that the amplitude-limiting means is responsive to motion or current of but one frequency, because it is responsive to the amplitude of its associated reed only, and that reed is so sharply tuned as to be virtually unaffected by the presence of the other eleven frequencies in the exciting current in its magnet 21. Thus I have provided; (*a*) a plurality of frequency-determining elements, namely twelve reeds, (*b*) a plurality of amplitude-limiting means, each responsive only to oscillations having the frequency maintained by that channel of which that means is a part, and adapted to limit the amplitude of oscillations of that frequency alone, to the exclusion of the other eleven, and (*c*) a common amplifying electron tube system substantially free from non-linear distortion, adapted to be excited by all of the plurality of frequency-determining elements by being connected at its input and output terminals to the several electro-mechanical channels and adapted to continuously maintain sinusoidal impulses in all of the several frequency-determining elements, each at its associated resonant frequency. The several frequencies thus maintained coexist simultaneously, and the frequency of potential and current maintained in the amplifier by a given reed is substantially the same as the natural frequency of that reed.

I have stated that each of the twelve reeds 1 is to be strongly resonant, in order that the twelve shall not interfere with each other's behavior. The ratio between two frequencies a semitone apart is roughly six per cent. Hence in a musical instrument it is necessary that each reed shall be sharply resonant enough so that it is virtually unresponsive to a frequency different by six per cent from its resonant frequency. This is a stipulation not very difficult to realize in practice in the sixteen-foot octave, and I have found by experiment that two reeds tuned a semitone apart will operate very successfully in conjunction with the same actuating amplfier provided they are not closely intercoupled mechanically by being mounted on the same supporting frame 2, or the like. Although their electrical output circuits are connected together to the input terminals of the amplifier, yet the mechanical load which such high impedance circuits impose upon the reed are very slight indeed, and the inter-reed coupling resultant from such a common electric connection may be expected to be very slight indeed. However, if it should be found that, under some other conditions than those which I set up experimentally, there should be appreciable or serious interference, it would be within the scope of my invention to associate six reeds with one amplifier, and the remaining six with a second amplifier. For example, the reeds for generation of C, D, E, F♯, G♯, and A♯ of the sixteen-foot octave might be actuated by the first amplifier, and the C♯, D♯, F, G, A, and B reeds of the same octave might be actuated by the second one. In such case, the frequencies of any two reeds associated with the same amplifier would differ by more than eleven per cent. Or the twelve generators might be divided into three or four groups, each group having a separate actuating amplifier.

Besides the twelve generators for the twelve tones of the sixteen-foot octave, a complete musical instrument should also have generators for tones of higher octaves. At 25, I illustrate six such generators. There may be as many as necessary for the gamut of tones desired. All of these may be constructed similarly to each other and to generators 24, except for the dimensional differences necessary to adapt each to the pitch it is required to generate, and except for other differences set forth below. I therefore consider it sufficient to illustrate only one in detail in Figure 1, and to illustrate others merely as "boxes," omitting still others altogether. Like parts in generators 24 and 25 bear like reference numbers. It is desirable that the generators for the octaves above the sixteen-foot octave shall each produce a frequency or pitch bearing a precise octave or multiple-octave relationship to its corresponding generator of the sixteen-foot octave. To this end, I have shown in one of the generators 24 a frequency-doubling electrode 20, insulatingly supported from casting 2. Due to its placement relative to the reed 1, it will be seen that electrode 20 will have a capacitance relative to the reed 1 which passes through a maximum value twice during each cycle or complete vibration of the reed; namely, when the reed passes through its position of rest or equilibrium. Moreover, due to the relative dimensions and placement of reed and electrode, virtually no odd partials of the fundamental reed frequency will appear in the potential which this electrode supplies to the amplifier 32, and only even partials will be present. Among these even partials, the second partial, or octave partial, will have the greatest amplitude; next to that of the second will be the amplitude of the fourth partial, and smaller still will be that of the sixth, and so on. Since the fundamental reed frequency is assumed to be 32.7 cycles for the generator illustrated in detail, the second partial or second harmonic frequency will be 65.4 cycles.

Electrodes 19 and 20 being connected together and to the input terminals of a common electron tube system 32, they are equivalent to a single electrode producing harmonic distortion and a complex wave form of input potential. This input potential, after amplifier 32 has suitably amplified the same, will appear in the current of magnet 21′ which forms a part of one of the generators 25. Most prominent among the components of that potential will be the first harmonic or fundamental, and the second harmonic. The reed 1′ which appears in the figure is assumed to be tuned to the octave frequency of 65.4 cycles, which is the frequency of eight-foot C. Being

coupled to reed 1 through the amplifier and through magnet 21', reed 1' will respond sympathetically to that frequency. It is to be understood that the generator 25 has no means for sustaining or limiting the amplitude of its own vibrations. Its oscillations are entirely forced, not self-maintained, ones, and are sustained continuously whenever reed 1 is oscillating. There is no necessity for self-maintenance or self-limiting in generator 25, since the frequency and amplitude of reed 1' are entirely determined by the frequency and magnitude of that current component which was supplied to magnet 21' by reed 1. Of necessity, then, reed 1' is at all times in oscillation at precisely double the frequency at which reed 1 oscillates.

At 20' I provide a pickup electrode insulatingly supported from the casting 2', like electrode 20 of generator 24. It will be evident from the symmetry in the relative shapes and placements of reed 1' and electrode 20' that this electrode will supply to amplifier 32 a wave form having only even partials of the 65.4-cycle frequency of reed 1'. Just as electrode 20 is able to supply to magnet 21' the frequency needed for maintenance of the reed 1', tuned an octave above reed 1, so electrode 20' is able to supply to the magnet of another of the generators 25 a frequency of double 65.4 cycles, or 130.8 cycles, which is that of C in the four-foot octave. I have considered it unnecessary to illustrate the last-mentioned generator, or others of its own or higher octaves. However, it is to be understood that such generators are to be constructed similarly to the generator 25 illustrated, except that their reeds are to be tuned to the respective frequencies and constructed accordingly. Their driving or actuating magnets 21' are to be connected in the output circuit of amplifier 32 between conductors 28 and 59, at the point marked "To other groups of magnets 21'."

I have explained that one of the generators or sources 25, that illustrated in detail, is actuated by currents supplied to it through the amplifier 32 by one of the generators 24. The output terminals of source 24 are accordingly connected through the common amplifier 32 to input terminals of source 25. Due to distortion or harmonic production in the mechanico-electric translating means, namely electrodes 19 and 20, source 24 is enabled to supply the frequency necessary to sustain vibration in a generator reed 1', tuned an octave above the reed 1. In like manner, this last-mentioned reed and generator in turn produce a twice-doubled frequency for the maintenance of another reed 1', omitted from the figure as superfluous so far as purposes of illustration are concerned.

I also illustrate five other generators 25, shown merely as "boxes." Each is adapted, like the generator 25 which appears in detail, to be actuated by one of the generators 24 of corresponding pitch name in the sixteen-foot octave. Thus, the C# generator 25 is actuated by current supplied from the C# generator 24, and so on. Moreover, each of the generators 25 is adapted to supply actuating current at the requisite frequency for a generator of corresponding pitch name in the four-foot octave. For reasons obvious from the foregoing, each of the generators 24 may be termed a master generator and each of the generators 25, whatever the octave in which the same occurs, may be termed a slave generator.

This process of actuating each generator from the corresponding one of the next lower octave can be carried on through several octaves merely by providing suitable connections to magnets, reeds, shields, and pickup electrodes of all the generators as will be evident from the legends at the lower lefthand corner of Figure 1, and at the center of said figure.

To make matters perfectly clear, I wish to point out that, from twelve master generators 24 and sixty slave generators 25, I may produce frequencies from sixteen-foot C to three-inch B inclusive in the amplifier 32. There will be seventy-two generators in all, whose reed frequencies range from sixteen-foot C to six-inch B inclusive. Each of the twelve master reeds 1 of the first or sixteen-foot octave has a fundamental-producing electrode 19, and a frequency doubling electrode 20, and the group of twelve master generators is thus capable of producing at the output of amplifier 32 the frequencies from sixteen-foot C to eight-foot B inclusive.

The remaining sixty reeds 1' have associated with them no fundamental-producing electrodes, but only frequency-doubling electrodes 20'. They are tuned to the range from eight-foot C to six-inch B inclusive, and thus they generate double these frequencies, or the frequencies of the range from four-foot C to three-inch B inclusive. Before the tones reach the loudspeaker, further doubling may occur as will be explained below, and hence the speaker may emit an additional octave of tones, ranging up to 1½-inch B.

It is to be observed that the seventy-two reeds 1 and 1' are all maintained in continuous vibration by the electron tube system whenever the musical instrument is to be ready for immediate use, whether any tone is actually being sounded by the loudspeaker or not. If any of these reeds were to stop its vibration, all those vibrating at frequencies exactly one or more octaves above that of the reed in question would soon cease to vibrate also, because their magnetic driving forces would have disappeared. Thus it would be out of the question with the arrangement of Figure 1 to play the tones at will from a keyboard by starting and stopping the vibration of the reeds 1 and 1'. Besides this, the ordinary reed is an extremely sharply tuned or strongly resonant vibratile element, especially in the lower octaves. Accordingly if one were to attempt to start and stop self-maintained reeds, such as the reed 1, by closing an electric connection associated with it through the intermediary of a key, it would be found that the reed would probably attain its full amplitude very slowly indeed, as pointed out in connection with electromagnetically maintained tuning forks by Severy, Patent No. 2,155,741, page 1, last paragraph. The response might be considerably accelerated by providing the reeds with considerable damping, as a solution of their differential equations will show. However, I prefer to control the tones from the keys in a manner discussed below.

At the lower right-hand corner of Figure 1, I show six slave generators 26. One of these appears in detail, and the other five may be identically construction except for such dimensional differences as are necessary to adapt each to its required frequency of oscillation. It will be seen that each has an electromagnet 21'', and that all of these are connected in series in the output circuit of amplifier 32. Also in series with these may be the magnets of as many other generators 26 (not shown) as may be needed to cover the gamut of tones desired from the instrument,

The electrostatic shields of all are to be grounded by the conductor 30, as shown.

Present in the magnets 21'' are all frequencies from sixteen-foot C to and including three-inch B, or eighty-four frequencies in all, originating at the generators 24 and 25. I provide eighty-four slave generators 26, each having a reed 1'' tuned to one of the above eighty-four frequencies. Each reed will thus be kept in continuous oscillation. In each source 26 I also provide a pickup electrode 19'' adjacent to the reed and insulated therefrom. In other respects, the oscillation generator 26 is quite similar to master generator 24, and it is accordingly believed that further detailed description of the parts will be superfluous. Like parts bear like reference numbers in the two generators, except for the distinguishing primes.

Suppose for the sake of definiteness that the reed 1'' illustrated in Figure 1 is tuned to 65.4 cycles. It will then respond to the frequency fed to amplifier 32 by electrode 20 shown near the upper left-hand corner of the figure. At the electrode 19'' may then appear the same frequency, since there is no frequency-doubling action inherent in its construction. However, this frequency will appear only if there is a difference of potential between elements 1'' and 19''. The means for providing this will be explained presently. Incorporated in each of the eighty-four generators is an electrode 19'' like that illustrated, and all are connected together and to the input of amplifier 66 by means of conductor 31 and condenser 9. The resistances 8 and 10 and condensers 23 and 9 at the input of this amplifier constitute a coupling network similar to that illustrated in my copending application S. N. 379,287. It will suffice to remark here that condenser 9 is a blocking condenser, 10 is a grid leak, and that elements 8 and 23 may have electrical magnitudes chosen so as to preserve quasi-linearity as explained in the afore-mentioned application and in my Patent No. 2,055,719. In addition, a proper choice of electrical magnitudes of the four elements of the input network and a suitable adjustment of electrodes 19'' relative to their respective reeds 1'' may serve to lend a suitable frequency-loudness characteristic to the tones of the loudspeaker. The amplifier 66 may have as many stages of amplification as required, and these may be of any type suitable to the purpose, as well known in the communication art. The details of the amplifier itself do not constitute a part of this invention. Connected to the output terminals of the amplifier I may provide a loudspeaker, not illustrated, the method of connection being familiar in the art. Together, amplifier and speaker and their associated coupling arrangements comprise a network adapted to utilize the electrical output of secondary generators 26.

It is desired that no alternating potential shall be produced by the electrode 19'' except when its corresponding pitch is selected by depressing a key of a keyboard, or the like. To this end, it is necessary that the network connected to elements 1'' and 19'' be such as to impose no polarizing potential difference between the two except when desired. Besides this, it is desirable that the adjacent surfaces of the two elements be coated with thin layers of some chemically inert, electrically conducting substance, such as graphite. I suggest coating them with the graphitic substance known as "Aquadag," or else spraying them with a thin layer of varnish or the like, and then dusting on graphite powder when the varnish has become tacky. In my copending application S. N. 355,792, a similar coating was suggested for a similar purpose on condenser electrodes having unidirectional instead of vibratile relative motion, and attention is directed thereto.

To polarize the reed 1'' from keyboards as desired for playing purposes, I provide a network comprising parts 6, 7, 6*a*, 6*b*, and 6*c*. This network is to be connected to the keyboards by means of the conductors 13*a*, 13*b*, and 13*c*, as illustrated and described in my copending application S. N. 379,287, which should be referred to for a complete description. The polarizing networks disclosed in Patent No. 2,216,513 to Hammond might be substituted, as will be understood. The keyboard or keyboards serves to connect these conductors to a suitable source of polarizing potential, as will appear from either the cited patent of application. Since the above-mentioned elements 6, 7, 6*a*, 6*b*, and 6*c* also appear in figures accompanying application S. N. 379,287, bearing identical reference numbers, it is believed superfluous to illustrate or explain the keying network in detail here. Its details do not form part of the present application.

As shown by the legend at the lower right-hand corner of Figure 1, one network consisting of elements 6, 7, 6*a*, 6*b*, 6*c*, 13*a*, 13*b*, and 13*c* will be needed for each of the generators 26, the present elements 1'' and 19'' being connected similarly to the stator and rotor electrodes respectively of the application cited.

I have already remarked that frequency doubling can be effected in the slave generators 25. It is also advantageous to so construct certain of the secondary slave generators 26 as to permit them to generate frequencies twice as great as the frequencies of their respective oscillatory elements. I may, as previously stated, provide eighty-four primary generators 24 and 25, and also eighty-four secondary generators 26, the latter group having constructions and dimensions suitable for oscillation at frequencies from sixteen-foot C to three-inch B inclusive, and having electrodes 19'' which do not introduce frequency doubling. The air gap between reeds 1'' and electrodes 19'' should also be such as to initiate relatively little harmonic distortion or upper harmonic production, as hereinbefore explained. In addition, twelve secondary generators will preferably be provided for generation of the twelve pitches of the 1½-inch octave. The reed of each would be tuned to a pitch or frequency of the three-inch octave, thus obviating the need for exceedingly small and light reeds. Adjacent to each reed would be an electrode like 20' in generator 25. This would double the frequency of the reed, and thus the tones produced by this uppermost octave of generators would lie in the 1½-inch octave, as desired. All twelve such secondary generators of the highest octave would be constructed identically with generators 25, except for the requisite dimensions needed to adapt them to the desired frequencies of oscillation and pitch of output potential.

It is within the scope of my invention to interchange the electrical connections to the reed and electrode in generators 25 and 26, in which case the reed would be connected to grid and the electrode to polarizing potential. A certain economy could be effected in this way in that a single reed 1'' could be made to feed to amplifier 66 two different frequencies, one in the three-inch and

one in the 1½-inch octave. To accomplish this, one might provide, adjacent to a reed 1'', an electrode 19'' for generation of the reed's fundamental frequency, and also a second one like electrode 20' in generator 25, for generation of twice the fundamental frequency. Either frequency could then be had from a single reed merely by polarizing the appropriate electrode.

For obvious reasons, the generators 24 and 25 are termed primary generators, while the generators 26 are known as secondary generators. It may be wondered why I have provided a primary set and an independent secondary set. This was not strictly necessary, and could be avoided by proper insulation, construction, and circuit connection, as will be evident to one skilled in the art. However, it was done in order that the primary set might be kept continuously polarized for the maintenance of continuous vibration, while the secondary set might be polarized only as they were to be played into the loud-speaker. It will be evident that a single set would have served both primary and secondary purposes provided the reeds were kept grounded at all times, and provided polarizing potential above ground were to be applied to the pickup electrodes, these same electrodes then serving also for feeding the alternating potentials to the amplifiers. Associated with each reed would be at least two pickup electrodes, one connected to amplifier 32 and the other to amplifier 66, the former being kept polarized at all times, and the latter being polarized only as its associated tone was to be played.

I prefer the disclosure illustrated in Figure 1, however, because the simpler one just described would doubtless have certain disadvantages. It would be more difficult to avoid key clicks when polarizing potentials were applied to those electrodes connected to amplifier 66, or when they were removed therefrom. The electrodes associated with the reeds of higher pitch would have to be quite close together for reeds of the usual dimensions, and careful electrostatic shielding would have to be provided. Otherwise, inductively produced tones might be heard in the loud-speaker even when no key is pressed. However, the simpler arrangement is not to be regarded as inoperative.

I have remarked above that the physical structure of variable impedance 35 in Figure 1 would be explained later. In Figure 2, I show one way in which such an impedance might be made. At 41 I show a conducting segment and at 42 an insulating segment in a rotating drum, as shown. The drum composed of these parts may be rotated by an electric motor, or by any other suitable means, not shown. At 40 I show a carbon brush adapted to maintain continuous contact with the inner portion of segment 41. At 39 I show five carbon brushes arranged at suitable intervals around the periphery. When only one brush 39 is in contact with the segment, only one circuit connection will exist through the device between terminals 36 and 37 via one of the condensers or other impedance elements 38; later, there will be two paths in parallel, as a second brush comes into contact; still later, there will be three, etc. By suitably choosing the electrical magnitudes of the several impedance elements 38, and by suitably locating brushes 39, the wave form relating impedance and time may be controlled. That decided upon will doubtless depend upon the designer. The drum will preferably be rotated at from five to ten revolutions per second.

The frequency of a reed or other mechanically vibratile member is proportional to the square root of the ratio of its stiffness to its effective mass. If the stiffness is increased, the frequency will be increased. Now, the stiffness exerts a force tending to restore the reed to its position of rest or equilibrium, substantially midway between the extremes of its oscillation. For reasonably small excursions of the reed, this force is at all parts of the excursion directly proportional to the displacement from the rest position. In other words, the reed follows Hooke's law to all intents and purposes. Any other force having the same properties will have the effect of increasing the apparent stiffness, and hence the apparent resonant frequency. That is, the apparent resonant frequency in the reed will be increased as compared with the natural frequency in the absence of such force, and the means for its production.

In Figure 3, I have provided means for exerting and utilizing such a force for vibrato purposes. At 43 I illustrate an electromagnet having a core 44 shaped as shown and positioned relative to a reed 1 in a manner suitable for the purpose. The reed and magnet are to be considered as constituting parts of a master generator 24. The core 44 exerts on the ferro-magnetic reed 1 a force tending to restore it at all times to its position of rest. Although this force may not be strictly proportional to the reed's displacement from this position, yet it will be nearly enough so for the purpose at hand. At any rate, its fundamental component will be in phase with the reed displacement; i. e., in time quadrature with the fundamental component of reed velocity. The force exerted by the magnet will necessarily be small as compared with that exerted by the actual elastic stiffness of the reed, since at most one would not wish to vary the pitch over a range of much more than a semitone or six per cent in frequency.

The core 44 may simultaneously serve not only to direct magnetic flux, but also to replace the electrode 20 in Figure 1, and I have accordingly illustrated it in Figure 3 as being connected by conductor 17 to the input grid terminal of amplifier 32.

I may vary the frequency by any means adapted to vary the current flowing in the winding of electromagnet 43. For example, the mechanism shown in Figure 2 would serve if elements 38 were resistors and if it were connected in series with a source of direct current and with the magnet winding. However, I prefer to employ the electrical network appearing in Figure 3. I may provide twelve magnet windings 43, each mounted adjacent to one of the twelve master generator reeds 1 of the sixteen-foot octave. All are connected with each other, with a source of direct potential 60, and with the plate-cathode circut of a triode 101, as indicated in the figure. The cathode is maintained at a suitable positive potential relative to the grid, as will appear. At 97 I show a neon lamp of the type suitable for use in a relaxation oscillator. It is supplied with direct current through a variable resistor 94, as shown. Shunted across it I show a condenser 95 and a resistor 96 in series. The elements 94 to 97 inclusive constitute a relaxation oscillator conventional in every respect except that the presence of the resistor 96 prevents the discharge of condenser 95 through the lamp 97 from taking place instantaneously, with a consequent undesirably steep wave front. If desired, a low pass

filter 99 may be provided to remove the higher harmonics present in the output of the oscillator. A blocking condenser 98 is provided to prevent the introduction of a direct potential onto the grid of tube 101.

By proper choice of the electrical magnitudes of elements 94 to 96 inclusive, the oscillator is adjusted to produce a subaudible fundamental frequency of from, say, five to ten cycles per second. By adjusting the potential divider 100, the variations in grid potential and of plate current in tube 101 can be regulated in magnitude. Accordingly, the magnetic restoring forces exerted on the reeds by the cores 44 are controllable, both as to vibrato frequency and amplitude. Provided the reeds of the sixteen-foot octave are not too sharply resonant (and this can be controlled by designing them for suitable damping by equipping them with air vanes or by making the insulators 3 of slightly soft rubber instead of Bakelite), the pitch of each reed will vary periodically at the vibrato frequency. It will be apparent that, since all of the generators 25 and 26 are slave oscillators, their frequencies will also vary periodically, again provided their reeds are not too sharply resonant.

It may be more pleasing to provide each master reed with a separate relaxation oscillator and tube 101, and to adjust the several oscillators to different vibrato frequencies. Or the C and C♯ generators might be varied from one relaxation oscillator, the D and D♯ generators from a second adjusted to another subaudible frequency of vibrato, and so forth. This arrangement would lend a greater warmth to the music performed than would a single relaxation oscillator, since it would then be unlikely that any two tones within a single octave which were played simultaneously would have the same frequency of vibrato. It is seldom that two pitches of tones a semitone apart are sounded at the same time.

In Figure 4, I show an alternative method for enabling the reed 1'' to effect capacitance variations. I have found that, if the heel of the reed is separated and insulated from an electrode 19' by a thin sheet of mica 46, the capacitance between reed and electrode will vary in accordance with the reed's vibration. The reed and electrode are insulated from the casting 2'' by means of Bakelite washers 3, and may be electrically connected in the circuit in the manner of reed 1'' and electrode 19'' in Figure 1.

In Figure 1, the coupling between a primary reed 1' and a secondary reed 1'' was accomplished electromagnetically through the magnet 21''. In Figure 5, on the other hand, I show how the coupling may be effected mechanically. In Figures 1 and 5, like parts bear similar reference numbers. As the reed 1' vibrates under the influence of its driving magnet 21', it exerts vibratory forces upon parts 2', 3, 47, 1'', and 22 to which it is attached. These forces cause a sympathetic vibration in the reed 1'', provided the latter is tuned to the same fundamental frequency as reed 1'. In consequence of this vibration, the capacitance between elements 1'' and 19'' undergoes periodic variation, just as in Figure 1. To protect reed 1'' from the electrostatic effect of the winding of magnet 21', I have provided a shielding metallic wall 48, which is grounded by being connected to the shield 22. This mechanical coupling above described permits one to dispense with the driving magnet 21'' of Figure 1. It is believed that the circuit for connecting up the elements of Figure 5 will be obvious from a comparison with Figure 1 without their being illustrated in detail in Figure 5. Whereas in Figure 1 a given primary reed actuates a secondary reed tuned to twice its fundamental frequency due to frequency doubling at the pickup electrodes, in Figure 5 the associated primary and secondary reeds must obviously be tuned to the same frequency. To permit closer coupling between reeds, casting 2' may be of aluminum.

I have found that there is a possibility of sufficient electrical leakage occurring between reeds 1' and 1'' over the surface or through the body of the intervening supporting insulators 3 to interfere in certain cases with the proper behavior of the device of Figure 5 unless precautions are taken to prevent this. Thus, reed 1' has at all times during operation a charge relative to ground, whereas reed 1'' is to be charged only when its associated tone is to be played, as explained in connection with Figure 1. Any leakage between reeds would charge reed 1'' so that its tone might sound continuously even when no key of the keyboard were pressed. To avoid this, I have provided a grounded metal washer 47, which I term a trap electrode, in the leakage path between reeds to intercept and conduct to ground such leakage as might otherwise flow between active electrodes 1' and 1''. A similar leakage between any of the reeds and associated electrodes in Figure 1 might interfere with proper operation there were it not for the fact that such leakage currents are intercepted by grounding the castings 2, 2', and 2'' through the screws by which their respective reeds are attached to them, as illustrated. This means for preventing leakage between a vibratile element and associated conducting elements, such as another reed or an electrode is novel, so far as I am aware. The assembly screws are insulated from reeds 1' and 1'' by sleeves around them, as previously explained in connection with Figure 1.

In Figure 1, I showed one means for limiting the amplitude of vibration of a reed or other vibratile element; namely, the contact 12 and associated parts. In Figure 6, I show an alternative means for accomplishing this end, which involves a novel shaping and positioning of the pickup electrodes calculated to effect a reduction in electron tube system input transduction factor with increasing reed amplitude, as will appear.

In Figure 6, the electrode 19 performs the same function as it does in Figure 1. Parts 5, 12, 15, and 18 of Figure 1 are omitted from Figure 6, and their function is assumed by electrode 19*a*. Electrodes 19 and 19*a* are connected together electrically, as shown, and in a sense constitute a common pickup electrode system. These two electrodes are both adjustable relative to the reed and are insulated from the casting 2, just as electrode 19 is in Figure 1. Other electric connections are to be carried out identically in the two figures. It has been considered unnecessary to illustrate these common features in detail in Figure 6.

The two electrodes, being both connected to an input terminal of amplifier 32, supply thereto an alternating potential having a complex wave form; that is, upper harmonics, through conductor 17. It will be observed that the phase of the fundamental component of potential contributed by electrode 19*a* will be one-hundred-and-eighty degrees out of phase with that contributed by electrode 19. For small excursions

of the reed, the potential from electrode **19** will considerably exceed that from electrode **19a**, because the effective area of the former is by far the greater of the two; enough greater, in fact, to overcome the effect of the somewhat greater air gap which exists between electrode **19** and the reed **1** when the latter is in its position of rest. Electrical connections being properly carried out, as well understood, the fundamental component of potential contributed by electrode **19** may be regenerative, and that of electrode **19a** may be degenerative. Since the regenerative effect will predominate for small excursions, the reed amplitude will build up for a time. Ultimately, however, as the amplitude increases, the degenerative effect of electrode **19a** will become nearly as great as the regenerative effect due to the relative magnitudes of the two air gaps as above mentioned.

When the reed amplitude has attained a magnitude such that the total feedback forces at fundamental frequency become only just sufficient to overcome the mechanical losses in the reed, the amplitude cannot further increase, and a steady state as regards amplitude is established. Thus, due to wave form distortion of a special sort, the type of generator of Figure 6 may be made self-limiting in amplitude, just as is that of Figure 1. I have found by experiment that such self-limiting action actually occurs provided the proper adjustments are made in the mechanical and electrical elements in the device.

Experiment has also demonstrated that, under such conditions, there is a strong second partial present in the potential fed to the amplifier **32** by electrodes **19** and **19a**. This partial, like the second partial created by electrode **20** in Figure 1, may be made effective to drive the reed **1'**.

A mathematical study of arrangements of this type will reveal that any arrangement and shaping of electrodes which can impart to the input of amplifier **32** a fundamental component of potential, the ratio of whose amplitude to that of the reed displacement increases sufficiently less rapidly than does the reed amplitude will limit that amplitude to a small enough value to prevent its striking the electrodes. Several alternative constructions having this property appear in Figures 7 to 10 inclusive. In each of the disclosures of Figures 6 to 10, likewise in that of Figure 17 to be discussed later, it will appear that the reed itself forms one electrode of a condenser, and that it has a definite capacitance with respect to at least one of the fixed electrodes or to the entire assembly of fixed electrodes. It will also be evident that the reed electrode and fixed electrode or electrodes are so shaped and so placed relatively that the input transduction factor which they contribute to their associated feedback channel decreases with increasing reed amplitude.

In order that the reed may be self starting, it is important in Figures 7 to 9 that the bottom edge of electrode **49** be about opposite the middle of the end of the reed **1**, as illustrated. It will be seen that the capacitance between reed and electrode will reach a maximum for some small upward excursion of the reed, and will become less as the upward excursion becomes greater than this, because the reed tip is traveling in a curved path, which increases the air gap between reed and electrode after the reed has risen to a certain point. Due to the shielding effect of the grounded electrode **50**, the capacitance between reed **1** and electrode **49** may be expected to be quite small for reed excursions downward from the equilibrium position shown. The resultant wave form of capacitance for sinusoidal reed vibration may be expected to be markedly non-sinusoidal, and to provide the proper amplitude-limiting action. Experiment has borne this out. The wave form has also been found to contain a marked second harmonic capable of driving the reed **1'** as explained in connection with Figures 1 and 6 above. Electrode **49** may thus be connected to conductor **17** in the manner of electrodes **19** and **20** in Figure 1, and may replace these electrodes and also the contact type of amplitude limiter of the foregoing figure.

Figure 8 is similar to Figure 7, except that the grounded electrode **50** has been omitted. Its shielding action has been found to be unnecessary under certain adjustments of air gaps and electric circuit elements.

Experiment has also shown that, by shaping the end of the reed **1** on a bevel as shown in Figure 9, the reed may be made to start itself more readily. The reason for this is not precisely known.

If there is any difficulty in starting the oscillation of the reeds in any of the disclosed devices, it will be found that oscillation may usually be initiated by opening and suddenly reclosing the output plate circuit of amplifier **32**, or by administering a mechanical shock to the reed. Either of these measures will usually shock excite the reed sufficiently so that it will maintain itself in continuous vibration electrically, and adjust itself automatically to its proper amplitude. It goes without saying, however, that the reed vibration should never be sufficient to cause it to strike any of the electrodes in any of the disclosed generators. When the reeds have once attained their steady states, they should be kept relatively free from shock, since experiment has shown that this may disturb the amplitude-limiting mechanism momentarily and may cause loss of control sufficient to cause contact between reeds and electrodes.

In Figure 10, I show other shapes and arrangements of electrodes which may be made to provide self-limitation of amplitude, together with a second partial or second harmonic of potential adequate to drive another reed, such as reed **1'** in Figure 1, tuned to double the frequency of reed **1**. Electrodes **19** and **51** in Figure 10 will feed to the amplifier **32** a non-sinusoidal potential of the proper wave form, provided they are shaped as shown, and provided their distances from the reed are properly adjusted, as determined by experiment. In view of the foregoing discussion, it is believed that further elucidation of Figure 10 is unnecessary, since the performance is qualitatively the same as that in Figure 7.

It will be evident that mechanico-electric translating means other than electrostatic ones might be used if properly placed to produce the requisite production of harmonics. For example, electromagnets having cores placed and shaped like the electrodes shown here would doubtless perform similarly.

In Figures 6 to 10, the limiting action is brought about due to the special shaping and positioning of the electrodes such that their capacitance to the reed is a non-linear function of the displacement of the latter, and that the wave form is one which changes in the proper manner with increasing reed amplitude. In Figure 11, there ap-

pears a purely electrical means for accomplishing the same function, employing a non-linear resistance; that is, one such that the potential drop across it is a non-linear function of the current through it. At 1 are two reeds like those similarly designated in the foregoing figures, and at 19 are their associated pickup electrodes. If these electrodes were to be directly connected to the input of amplifier 32, and if the currents fed back to their magnets (as shown in Figure 1 but not in Figure 11) were sufficient to start the reeds in vibration, it would be found that the amplitudes of reed vibration would build up until one or the other of the reeds struck its associated electrode. Such wide excursions may be prevented by employing the thermionic diodes 56, potential source 60, and adjustable resistors 57 connected to conductor 17 and thence to the input of amplifier 32 as depicted. Due to the source 60, the cathodes of the diodes conduct no current unless potential is supplied from the reed sufficient to overcome this bias. The circuit is similar to that of the delayed diodes used for automatic volume control in many radio receivers. For small reed amplitubes, the potential peaks attained by electrodes 19 will be insufficient to overcome the delay bias contributed by source 60. Thus, provided the feedback action driving the reeds is correct in magnitude and phase, the amplitude of either of the reeds will continue to build up until the diode associated with that reed conducts current at the peaks of potential.

During periods of conduction, the diode partially short-circuits its associated electrode 19 to ground. It is prevented from greatly influencing the potential of any of the other electrodes 19 which are not associated with it, due to the decoupling action of its associated resistor 57. The presence of the resistors also enhances the short-circuiting action. The fundamental component of potential present at electrode 19 is affected by the short-circuiting action in such a manner as to set a limit to its magnitude, and therefore to that of the reed which it controls. It is to be noted that the diodes are not a part of the feedback amplifier 32, but that each is part of an individual feedback channel. They perform no amplifying function whatever, their action being purely a limiting and wave form-distorting one. Due to this distortion, a second partial or harmonic appears at the input and output terminals of amplifier 32, which may serve to drive reed 1' in the manner explained above.

All of the amplitude-limiting means described above operate by reducing the ratio between the amplitude of the fundamental component present in the input potential to the feedback amplifier 32 and the amplitude of the fundamental component of velocity present in the resonant element (the reed). This ratio between amplitudes I term the electron system input transduction factor, for the sake of brevity. In the cases discussed, the limiting of feedback occurs between the reed and the amplifier input terminals. Hence the appropriateness of the term adopted.

There is another type of device capable of limiting the individual amplitudes of the several resonant elements in a somewhat different manner from the above. This device appears in Figure 12. In this case, the output terminals of amplifier 32 feed the voice coil of a loudspeaker cone 54 through the intermediary of an output transformer 55. The speaker will also have a field magnet, which is not shown in the figure, but which is constructed like that of the usual dynamic loudspeakers used in radio receivers. As will appear, any other type of loudspeaker or electromagnetic sound-translating means would serve if sufficiently free from non-linear distortion.

To explain the operation of this device, I assume that one of the reeds 1, shown in end view, has been started in vibration in some way, as by a mechanical shock. Being connected to source 60 through a conductor 27' and the metal top of wind chest 51, the reed is held above ground potential as in foregoing figures. In consequence of the vibration of the reed, an alternating potential at the fundamental frequency of the reed is fed to input terminals of amplifier 32 in the manner explained hereinabove. A current having the same fundamental frequency accordingly appears in the voice coil of the cone 54, and the cone is maintained in vibration thereby. The rim of the cone is permanently screwed to the bottom of the wind chest 51. This chest may be a box made of wood except for its top, which is of metal. Its bottom has a suitably large hole over the cone so that the pressure in the chest varies periodically in accordance with the vibration of the cone.

It is to be understood that there may be twelve reeds, one tuned to each of the twelve tones of the sixteen-foot octave, as in Figure 1. Of these, only two are illustrated as representative of the group. The remaining ten may be located to the right of the two, or behind them in the drawings. All of the electrodes 19 may be connected to the input of amplifier 32 in the manner of the two shown. I have shown a portion of the top of the chest 51 as broken away. This was merely to avoid showing more reeds than necessary for an adequate disclosure, and I prefer to have the chest entirely closed off from the outside air except for such orifices as occur around the reeds and perhaps around the speaker cone. This will aid the cone in establishing the greatest possible variations in air pressure within the chest for a given amplitude of cone vibration.

Since a given reed 1 is subjected on its lower face to an alternating air pressure, it will tend to be vibrated thereby. Provided feedback is sufficient in magnitude, and provided phase relations are correct for regenerative feedback as above explained, the reed may be maintained in continuous vibration at its natural or resonant frequency.

Each of the reeds consists of a tongue and a frame, being constructed precisely like the reeds of the well-known harmonium. However, the tips of the tongues are bent somewhat differently than is common in the harmonium, so that they occupy a position relative to their frames as illustrated in the figure. Since the reeds need not be subject to magnetic forces, they may be of brass, like harmonium reeds.

In the upper part of the wind chest I have provided a plurality of reed cells 52, each having a reed mounted in its upper wall, and each having an orifice 53 through which it receives an alternating supply of air from the main body of the chest. Except for its orifice and for the slots between the tongue and frame of its reed, each cell is completely closed.

For small excursions of vibration of any given reed, the above-mentioned slots will be quite

small in cross section, and will provide but little opportunity for the escape of air. However, for sufficiently large excursions, these slots will be seen to become quite large. Provided the orifice **53** is made sufficiently small, it will provide an appreciable acoustic impedance to the alternating current of air passing through it between its associated cell and the main body of the wind chest. Thus, for large excursions, the amplitude of the fundamental component of alternating air pressure in the cell will be reduced relative to that in the main body of the chest. This will serve to limit the amplitude of reed vibration, as will be evident.

Provided the volume of air in the main body of the chest is made large enough relative to that of each of the cells, and provided the acoustic impedance of each of the orifices is made sufficiently great, the several reeds will be effectively decoupled from one another, and they will not appreciably affect the amplitude or frequency of vibration of one another.

Thus, I have shown an acoustic means for maintaining the reeds of the sixteen-foot octave in continuous vibration or oscillation, and for individually limiting the amplitude of each. This scheme has been proved by experiment to be operative. It is evident that these reeds may be made to supply second partial potentials for driving reeds of the eight-foot octave, as in Figure 1. To accomplish this, one need only mount, adjacent to each of the reeds **1**, an additional electrode like **51** in Figure 10, and connect the same to conductor **17** as in that figure.

I have not shown electrodes **51** in Figure 12, because to do so would crowd the drawings and because the method of mounting and connecting them should be evident in the light of foregoing figures. In Figure 12 I have, however, shown conductors **27** and **27'** which conduct current from source **60** to groups of magnets **21** and **21'** respectively, in the manner of Figure 1. I believe that, in view of Figures 1 and 12, it will be clear that one may combine into a single network a plurality of self-maintained or master reeds **1** which are acoustically coupled to the output of the electron tube system and acoustically limited, and which in turn electromagnetically drive slave reeds **1'** and **1''**, being coupled thereto through the intermediary of a common amplifier **32**.

In contradistinction to the limiting means of foregoing figures, that of Figure 12 performs its limiting function by reducing the ratio between the amplitude of the fundamental component present in the resonant element and the amplitude of the fundamental component present in the output potential from the amplifier **32**. This ratio I term the amplifier output transduction factor or electron tube system output transduction factor. That is, there is a reduction in the efficiency of coupling between the sound translating device **54** and the vibratile element. In other words, the coupling which is reduced is that between the electron tube system output terminals and the reed or resonant vibratile element.

In Figures 13 and 14 appear alternative means for actuating secondary reeds **1''** from actuating amplifier **32**. Element **29** is an attenuator, and **30** and **107** are coacting pedal-operated contacts for expression control, as known in the art. Continuously present in the output of amplifier **32** are a plurality of alternating potentials, each having the frequency of one of the reeds **1** or **1'**, as seen from Figure 1. A conductor **28** supplying such potentials appears both in Figures 1 and 14. The direct potential also present at the output is stopped off from the attenuator by blocking condenser **58**. A resistor **102** may be included if needed to prevent the attenuator from robbing current from magnets **21** and **21'**, which are also to be connected to conductor **28** in Figures 1 and 18.

When the performer presses a keyboard key **106**, Figure 13, thus closing key contact **104** to conductor **105**, a connection is established from attenuator **29** via contacts **30** and **107**, conductor **105**, key spring **104**, decoupling resistor **103**, and elements **13a** and **6a** to a magnet **21''**. Only one such connection is illustrated, and that one quite conventionally, since details of the keying and stop circuits per se do not form a part of this application, but such circuits are claimed only generally and in combination with other parts. The same keying connections can evidently be applied to Figure 1 for the same purpose. The keying and stop circuits of a number of other applications or patents may be employed in the present environment, if adapted along lines evident to those working in the art. See, for example, Re. 19,702 to Bourn, Figures 1 to 3, or my copending application S. N. 379,287, filed February 17, 1941, Figures 1 to 3. It will be understood that the electrical magnitudes of the circuit elements present in these references may have to be altered to suit present needs. In particular, condensers present in the cited references may have to be reduced in capacitance or eliminated entirely to adapt the networks to alternating currents.

In Figure 1 of my earlier application, it will be seen that the polarizing potential is supplied to the stators of alternators **1A** to **1L** through conductors **13a** to **13c** and resistors **6a** to **6c**. These same conductors and resistors appear with the same reference numbers in the present Figure 13. However, in the present instance, instead of direct currents, they carry alternating currents supplied by amplifier **32**, as has already been stated. Also, instead of being connected to ground through a resistor **6** and condenser **7**, as in application 379,287, they are connected in the present Figure 13 through the windings of magnets **21''**.

A study of the two applications will reveal that, when the appropriate key and stop contacts are closed, a plurality of alternating currents having the frequencies of musical tones will flow in a selected one of these magnet windings. There will also be present a direct current supplied from source **60**, Figure 13. The magnitudes of these currents will be controllable by proper key and stop manipulation in the manner set forth in the earlier application. In view of all this, it is believed unnecessary to provide the present application with a drawing and detailed description of the entire complicated network.

In Figure 13, reeds **1''** are mounted adjacent to magnets **21''**, as in Figure 1, each reed being tuned to a tone of the musical gamut, as explained. Being sharply tuned, each reed will respond to that frequency in its magnet to which it is tuned, but not appreciably to any other present therein, and the steady state amplitude attained by the reed will be neary proportional to the amplitude of the component to which it is tuned. In other words, the reed amplitude (rather than reed polarizing potential as in Figure 1) will be controllable by the manipulation

of selectors such as the keys and stops mentioned in the previous paragraph.

Adjacent to each reed 1'' is a pickup electrode 19''. This passes on to amplifier 66 an alternating potential nearly proportional to reed amplitude, in the manner explained in connection with Figure 1. The output potentials of reeds 1'' are thus utilized in a common network comprising an amplifier 66.

Continuously, whether keys are pressed or not, amplifier 32 simultaneously amplifies the plurality of frequencies originating at primary sources 24 and 25. When current is admitted to a magnet by closure of a key contact, the alternating actuating potential and current therein will attain their steady states in a comparatively short interval of time. However, the amplitude of reed oscillation which results from the current in a given magnet 21'' of a secondary source or generator 26 need not build up to its proximate steady state in so short an interval, but may be made to build up gradually in the manner characteristic of the pipe organ if desired, by proper choice of reed damping, as will be well understood. See Patent No. 1,929,027 to Miessner, page 1, lines 65 to 77. In like fashion, the decay of the tone may also be rendered organlike.

In the foregoing figures, I have shown a plurality of mechanically resonant or oscillatory elements, each tuned to a different individual frequency of a musical scale, and each provided with individual means for automatically limiting the amplitude of its fundamental component, all of the resonant elements being maintained in continuous vibration by means of a common electron tube system. I may also employ in a similar fashion a plurality of electrically resonant elements, each provided with its individual limiting means and all being maintained in continuous electrical vibration by a common amplifier.

Figure 15 shows a portion of such a network. Elements 69 and 74 are respectively a variable condenser and the secondary winding of an iron-cored audio frequency transformer. In series with each secondary winding is a small incandescent lamp 73 having a tungsten filament. Through conductors 76, the two tuned tank circuits are connected to variable resistors 57 and thence to the grid of an amplifying triode 90, just as in Figure 11. The triode is to be regarded as illustrative of a more complex amplifier having more than one stage, although in certain instances one stage will doubtless prove adequate. The plate of the triode shown, or the plate of that which constitutes the last stage in any case, is connected in series with the primary windings of the transformers 74 and thence through the source of B potential 60 to the cathode of said triode. Of course I may use as many tank circuits as are necessary for the several tonal pitches required, and all may be connected in the manner illustrated.

The several electrically oscillatory or resonant elements, comprising inductances and condensers, are to be loosely coupled to the plate circuit of the triode by a suitable choice of turns ratios and coupling coefficients of the transformers 74. They are also to be loosely coupled to the grid and to each other by making the resistances of resistors 57 sufficiently large. Nevertheless, the phase and magnitude of feedback are to be such as to maintain all of the tank circuits in continuous electrical vibration or oscillation, as will be understood from the foregoing discussion.

It is to be remembered that that portion of the network wherein is simultaneously present potential at the several generated frequencies is to be as free from non-linear distortion as possible. Accordingly, the tube 90 is to be operated at all times below the point of overload, and its type and operating potentials should be chosen in accordance with this requirement.

As in foregoing disclosures, there must be means individual to each of the several generated frequencies which serves to limit the amplitude of its associated frequency, and which is controlled substantially entirely by the amplitude of a potential or current at its associated frequency. In Figure 15, such means is found in the lamps 73. It is a well-known characteristic of a tungsten filament that its electrical resistance increases markedly with increasing temperature, particularly in certain temperature ranges. In other words, its current and voltage are non-linearly related when one considers the values of each averaged over long periods such that the filament temperature has time to change, because the temperature is a function of the current in the filament. For a given potential impressed by the tube 90 on the primary winding of one of the transformers 74, the potential which its associated tank circuit supplies to the grid of the tube will depend upon the resistance of the associated lamp; the greater the current in the lamp, the hotter it will become, and the less will be the grid potential. It will be seen from this that if, by adjusting a resistor 57, the feedback to its associated tank circuit be made only a little more than sufficient to initiate oscillation with the filament cold, the increasing temperature and resistance of that filament as oscillation builds up may serve to limit the amplitude of current in the tank to a value which will not overload the tube 90 or any other part of the network wherein there is present energy associated with a plurality of different frequencies.

It is to be understood that a given tube 90, if used in a musical instrument, need not coact with all the tuned circuits of the sixteen-foot octave. If desired, the tones may be divided into two or more groups such that a given tube does not serve to maintain any two adjacent semitones, after the manner above explained in connection with reed oscillators.

In Figure 15, the lamp resistance does not change materially over a single alternating current cycle, due to thermal lag, and there is thus no production of second partials for producing forced oscillations in tuned circuits of octave frequency. Hence every tuned circuit present should comprise its own amplitude-limiting lamp 73.

In Figure 16, I illustrate another means for independently limiting the amplitude of energy or potential associated with each of the several fundamental frequencies produced by the multi-frequency generator. Whereas in Figure 15 the non-linear resistance used as a limiting means consisted of a lamp in series with a leg of the tank or tuned circuit, in Figure 16 such means or resistance consists of a diode 55 shunted across the tank circuit. As in Figure 11, there may be one such diode associated with each of the resonant or frequency-determining elements. In Figure 11, the frequency-determining means is the reed 1. In Figure 16, it is the combination of elements 69—74. Without illustrating a plurality of diodes and tank circuits in Figure 16, it is believed that the operation of the diodes will be

clear in the light of Figures 11 and 15. Each of the diodes 56 may be connected to one end of an associated individual resistor 57, and the several resistors may be connected at their other ends to one another and the amplifier input terminal, as in Figure 11. The primaries of the several transformers 74 may be connected in series with the output circuit of the amplifier, as in Figure 15.

With some reduction in the number of reeds necessary as compared with the disclosure of Figure 1, I may employ high frequency energy in the maintenance of continuous reed vibration, as shown in Figure 17. At 68 appears a source of supersonic potential, coupled through a high-frequency transformer 67 to a tuned circuit consisting of the secondary winding of that transformer and a tuning condenser 69. Through condensers 61, the tuned circuit is able to supply high frequency current to the reeds 1 and 1'. This current returns through a portion of each of the potential dividers 6 to ground and thence to the tuned circuit. By virtue of the potential drop in these portions of the potential dividers, each of the reeds will have a high frequency potential differing from that of ground.

Assume one of the reeds 1 to be in vibration. Through the capacitive paths between the reed and the adjacent electrodes 19, and via the conductors 17 and condensers 63, high frequency current will be supplied to the variable condenser 69 located in about the center of the figure. Another high frequency path from the reed to the same condenser exists, via the capacitive path between the reed and the electrode 49, thence through condenser 62, one of the conductors 17, and one of the condensers 63.

Connected across the condenser 69 are a grid leak 91 and the input terminals of a conventional radio frequency amplifier 70. The grid leak may be replaced by an inductance if desired, and condenser 69 adjusted for resonance at the frequency of the source 68. Receiving high frequency potential from that amplifier is a conventional demodulator 71 which supplies audio potential at the frequency of the reed 1 to the input terminals of audio amplifier 32. Together, amplifiers 70 and 32 and demodulator 71 comprise an amplifying electron tube system connected at its output to driving magnets 21 and 21'.

An inspection of the network will reveal that it thus far differs essentially from certain foregoing disclosures of this application only in that the reeds or resonant mechanical elements 1 and 1' are polarized with high frequency or supersonic potential instead of with direct potential, and that a demodulator and radio-frequency amplifier are added to complete the feedback network. It will also be understood that, in consequence of the feedback channel via radio frequency amplifier, demodulator, audio frequency amplifier, and driving or actuating magnets, the reeds 1 may be maintained in continuous vibration or oscillation by proper attention to phase and magnitude of feedback factor. In the manner of foregoing figures, particularly Figures 7 to 10, the variation of capacitance between the reeds 1 and their associated electrodes 19 and 49 will be such as to limit reed amplitude and to produce a strong second harmonic or partial for the maintenance of vibration in reeds 1'.

In Figure 1, the reeds 1'' could be polarized from a keyboard through resistors 6a to 6c. A similar polarization can occur in Figure 17, except that in this case it is the reeds 1 and 1' which may be thus polarized. Taking one of the reeds 1 for the purpose of explanation, suppose it to have been thus polarized. So far as direct or audio currents are concerned, the condenser 7 is to all intents and purposes connected to ground at one of its terminals, and thus may serve a purpose identical with that in Figure 1. The condensers 62 are assumed to be of sufficiently small capacitance so that they will not efficiently transmit audio frequency currents, although they may be efficient paths for currents of high frequency. In the discussion which follows, the electrodes 49 may accordingly be disregarded. The audio potentials present at the two electrodes 19 will be 180 degrees out of phase with each other in consequence of their opposite positions with respect to the reed 1.

I wish it to be understood that the two electrodes 19 are to be identically constructed and to be adjusted to positions equidistant from the rest or equilibrium position of the reed. Their potentials will consequently not only be 180 degrees out of phase at the fundamental frequency, but they also will be equal in magnitude and identical in wave form. The two potentials are supplied respectively to the two grids of a double triode 64, as shown, and the plate circuits of this triode are connected in conventional push-pull fashion to the input terminals of an amplifier 66. The amplifier, in turn, feeds a loudspeaker 73.

Other reeds 1' may supply tones of their respective frequencies to the same amplifiers and loudspeaker, as will appear from the figure. Through the use of high frequency feedback means for the maintenance of continuous reed oscillation, I have enabled the network of Figure 17 to deliver selected tones directly from the primary reeds 1 and 1', without the necessity for secondary reeds 1'' as in Figure 1.

In Figure 18, I show a reed assembly wherein the actuating magnet 21, by virtue of its placement relative to the reed 1, effects an automatic limitation of the reed amplitude. The reed 1, through a connection not shown in Figure 18, is to be kept charged by connection to the source 60, just as in Figure 1. The tip 44 of the magnet core serves its usual purpose of a directing flux, and also as a pickup electrode, as in Figure 3. Due to its symmetrical placement relative to the rest position of the reed; that is, midway between the extremes of reed oscillation, only even harmonics or partials of the reed's fundamental frequency will appear at the conductor 17. As in Figure 1, this conductor is to be connected to the input of amplifier 32 and the winding of magnet 21 is to be connected to its output.

By suitably choosing the number of stages of amplification in amplifier 32, the magnitudes of the coupling impedances at the amplifier input and output, the type of coupling between its stages, and perhaps other network parameters, the phase of the maxima of force exerted by the magnet upon the reed may be shifted at will, as will be evident to one skilled in the communication art. There will be two such maxima per complete oscillation of the reed, due to the doubling of frequency just mentioned. These maxima should occur while the reed is moving toward its position of rest, one occurring when it is above that position and moving downward, the other occurring when it is below that position and moving upward. In both cases, the force will be such as to partially or entirely overcome the damping forces of the reed, and will therefore tend to maintain the reed in vibration. In other words,

they will decrease the effective damping of the reed, although they may also tend to affect its frequency of vibration slightly. To prevent the frequency shift from being unduly great, the reed should be as sharply tuned as possible.

If such forces are correct in phase and sufficient in magnitude, the reed amplitude will continue to build up as hereinbefore explained. It will be seen, however, that, the greater the reed excursion carries it from the tip of the magnet, the less effective will be the magnetic forces upon it, at least beyond a certain critical excursion. Likewise, the less will be the interelectrode capacitance between the pole tip and the reed tip. In other words, the less will be both the electron tube system input transduction factor and also its output transduction factor as above defined. By suitably shaping these two tips, and by properly adjusting the phase and magnitude of amplification factor, as best arrived at by experiment, the reed amplitude may be made to limit itself to a critical value.

By varying the direct current in the winding of magnet **21** at a slow, subaudible frequency, a vibrato effect may be produced in the disclosure of Figure 18, as described in connection with Figure 3.

I have shown that the output potential of amplifier **32** will contain a strong second harmonic of fundamental reed frequency due to the frequency-doubling properties of the pickup electrode **44** in Figure 18. This second harmonic may be made to drive an octave-tuned reed **1'** as in Figure 1 by connecting the driving magnet **21'** for that reed to the output terminals of amplifier **32** in the manner of Figure 1. Reed **1'** and magnet **21'** are to be placed relative to each other as illustrated in that figure. Further reeds **1'** and **1''** may be driven from the output of the amplifier in the fashion shown in the same figure. It is believed that this will be well understood without illustration in full in Figure 18. Of course, if the amplitude-limiting scheme of Figure 18 is employed, that of Figure 1, utilizing the contact **12**, will be unnecessary.

Classified from one point of view, the amplitude-limiting means of this application fall into two groups; namely, those which operate by virtue of a variation in the amplifier input transduction factor, and those which operate by virtue of a variation in the amplifier output transduction factor with increasing amplitude in the resonant element. In the first class fall the means illustrated in Figures 1, 6 to 11 inclusive, 15, 16, and 17. In the latter class are the means of Figure 12. The disclosure of Figure 18, it will be recalled, typifies both types of variation.

One might also classify the limiting means from a second viewpoint, namely; (*a*) those of Figures 1 and 15, wherein the transduction factor is reduced without distortion of wave form of output potential, and (*b*) those wherein distortion accompany such reduction as in the figures other than 1 and 15.

In Figures 1, 3 to 13 inclusive, 17, and 18, the resonant frequency-determining element is a reed, although it may clearly be replaced by any of a number of types of mechanically tuned members, as stated hereinabove; in Figures 15 and 16, on the other hand, the resonant frequency-determining means comprise an inductance and capacitance, and the tuning is electrical in nature. In either case, the wave form of oscillation in such frequency-determining means, whether such oscillation or vibration be electrical or mechanical, is quite accurately sinusoidal, due to the resonant properties just referred to, provided, of course, that the amplitude is not permitted to become too great. On the other hand, the wave forms of current in the network apart from the frequency-determining means is, or may be, markedly non-sinusoidal. In fact, in the sustaining amplifier or electron tube system **32**, which is a part of the sustaining network, there are present a plurality of different frequencies, because the amplifier is common to a plurality of different resonant frequency-determining elements, each of the latter being adapted for the continuous generation of a different fundamental frequency. Also included in the network as a whole are a plurality of amplitude-limiting means, each associated with a different one of the frequency-determining elements, and with a different one of the fundamental frequencies, as will be evident. All the above variants are comprehended within the scope and spirit of my invention.

In accordance with my invention, primary oscillatory reeds or other resonant elements of octaves higher than the first (in the embodiment illustrated, octaves higher than the sixteen-foot) octave are not self-driven or self-maintained, but are maintained in continuous oscillation at their respective natural frequencies by means of harmonics or partials intentionally set up by generators of some lower octave. When employed in a musical instrument, this insures a perfect octave relationship between the pitches or frequencies of tones of the same name in different octaves, such as those of pitch G in the sixteen-, eight-, four-, and two-foot octaves, for example, without the necessity of tuning the resonant elements of any octave except the lowest. This is a distinct advantage from the standpoint of maintenance of such an instrument. However, if the resonant means for the octaves above the lowest get seriously out of proper tune, as might occasionally happen, their amplitudes will become less, due to their departure from resonance with the periodic force which is actuating them. This will be especially true if they are very sharply resonant. It would thus seem advisable not to make the reeds or tuned circuits of the upper octaves too sharp, but to somewhat increase their damping if need be, by the addition of mechanical or electrical resistance. Electrical resistance may be provided by inserting a resistor in the tuned circuit. Mechanical resistance might be increased, for example, by making the insulating washers **3** of slightly soft material, such as a semi-hard rubber, instead of Bakelite as above recommended, or by adding damping vanes, as is well known in the art.

In the even-tempered musical scale, the pitch of some of the harmonics or partials of one tone will lie very close to that of other tones. For example, the third harmonic of sixteen-foot C differs but slightly in frequency or pitch from the fundamental of eight-foot G, and the fifth partial of sixteen-foot C but slightly from the fundamental of four-foot E. Such harmonics, if sufficiently prominent in the electron tube system, might interfere with the proper operation of the resonant means of such higher octaves, causing frequency instability and interlocking as discussed in an earlier part of this specification. For example, in Figure 1, it might be expected that the reeds **1'** and **1''** tuned to eight-foot G would behave erratically because they would re-

spond simultaneously to the second partial of sixteen-foot G and to the third partial of sixteen-foot C. However, it is not essential to the proper operation of the device that any partials of a given reed or other resonant means except the second partial be present in the amplifier output. Hence, amplifier overloading, which might produce unwanted partials, is to be avoided. Moreover, the adjustments, shapes, and positioning of electrodes such as **19** and **20** must be made such as to prevent too great a prominence of such unwanted partials, as will be well understood. Besides, the magnetic circuits of the magnets **21'** and **21''** should be rather open, so as to prevent the development of such harmonics other than fundamental and second, as well as other sum and difference frequencies, as pointed out above. The amplitude-limiting means of Figures 1 and 15 do not function by the development of harmonic distortion, and thus I regard them as preferable from the standpoint of undesirable interference between generators. In Figure 1, for example, only even harmonics need be present in a strength comparable with that of the fundamental, and the second can be made by far the most prominent of these by suitably shaping and mounting the electrodes as best learned from experiment.

Those self-maintained resonant or tuned oscillatory elements which appear in all figures except Figure 18, whether such elements are electrically or mechanically oscillatory, are maintained in continuous oscillation by producing in the amplifier **32** a potential having a frequency which is the same as the fundamental frequency of the oscillatory element. In Figure 18, on the other hand, the frequency in the amplifier is twice that fundamental natural frequency, and a "halving" of frequency occurs at the air gap between the actuating magnet **21** and the reed **1**. I consider, however, that there is a unity of principle in all such disclosures, because in all of them the frequency in the sharply resonant or oscillatory element bears a harmonic relationship to that in the electron tube system. Thus, in Figure 18, the frequency in the tube system is the second harmonic or partial of the fundamental frequency of the oscillatory element. In the other disclosures, the potentials in the tube system which serve to maintain oscillation have the same frequency as the natural frequency of the oscillatory element; that is, the tube system frequency is the first harmonic or partial of the fundamental frequency of the oscillatory element. I have phrased certain of the claims in accordance with a recognition of this unity of principle; whether the harmonic in question is the first or second, a harmonic relationship nevertheless exists.

Many of the details of my invention are applicable to other forms of the parts with which they are associated. For example, in a given musical instrument, some of the vibratile elements might be reeds and some might be tuning forks or bars or tuned electric circuits, as will be evident, without departure from the spirit of my invention.

It will also be evident that forms of reed actuation other than electromagnetic might be employed within the spirit of my invention as, for instance, piezoelectric means. Similarly, pickup means might be of the photoelectric or electromagnetic form. Whatever the form of actuation or pickup, however, it is essential that individual limitation of amplitude be provided for those tuned elements which maintain themselves in oscillation.

Where the claims include a source of potential, I do not mean to confine myself to a single source, since it is obvious that a plurality of polarizing sources or sources of alternating potential are equivalent in general to a single source, and that separate polarizing potential sources may be used for the several oscillatory elements without the exercise of further invention.

Where a claim or claims include "selectors," "electric connections each closable to connect," or the like, I mean to include switches couplers, stops, keys, or similar instrumentalities except as further limited by the language of the claim. Except when further limited, as by the word "conductively," or the like, I also do not mean to be limited to devices which make electrical contacts such as a switch. Such devices may bring electrical parts into inductive relationship, and the electrical influence through such selectors may be via a solid or fluid path.

In the claims in which I use the term "network" or "circuit," unless further limitations appear, I mean to cover all conductors, or electrical networks, however complex, in which there can be an appreciable transfer of electric charges by metallic, galvanic, ionic, or electronic conduction; I mean to cover also such instrumentalities as condensers, transformers, and gaseous, vacuum, and photoelectric tubes.

Wherever I use the term "electron tube," I mean to comprehend tubes or valves of either the gaseous or vacuum type.

Where I refer to a "feedback channel" or the like, unless further limitations occur, I mean to include channels which are purely electrical, partially mechanical and partially electrical, partially acoustic and partially electrical, and so on, and there may be a translation from electrical into mechanical or acoustic oscillation and back again into electrical oscillation within such a channel.

Unless further limitaitons appear, where I recite "means for coupling together," I mean to to include mechanical, electrical, or other means adapted to the purpose specified.

The drawings and description illustrate and describe what I now consider to be preferred forms of the device for production of alternating currents or potentials for any purpose, by way of illustration only, while the broad principle of the invention will be defined by the appended claims. In these claims, where reference is made to a "source of alternating potential" or the like, it is not to be inferred that the production of such potentials is the ultimate purpose of the instrumentality referred to. The ultimate purpose may, for example, be the production of musical tones.

I claim:

1. A multi-frequency oscillator, comprising: an amplifying electron tube system; having an input circuit and an output circuit; a plurality of non-linear feedback channels each electrically connected to said input circuit and each, in cooperation with other parts of said oscillator, maintaining in said system continuous electrical oscillation at a single fundamental frequency and each, by virtue of its non-linearity, generating in said system an upper harmonic of its fundamental frequency, the oscillations maintained by the several channels coexisting simultaneously and having frequencies which differ from each other; constituting a part of each of said channels, an element sharply resonant to substantially the frequency of its associated upper harmonic and maintained in oscillation by the energy in said

channel; also constituting a part of each of said channels, individual means limiting the amplitude of those oscillations in said system which are maintained by the channel which comprises said means, each said individual means being actuated only by oscillations having a harmonic relationship to those maintained by that channel of which that means is a part.

2. A multi-frequency oscillator, comprising: an amplifying electron tube system having an input circuit and an output circuit; a plurality of non-linear feedback channels each electrically connected to said input circuit, each, in cooperation with other parts of said oscillator, maintaining in said system continuous electrical oscillation at a single fundamental frequency, and each, by virtue of its non-linearity, generating in said system an upper harmonic of its fundamental frequency, the oscillations maintained by the several channels coexisting simultaneously and having frequencies which differ from one another; constituting a part of each of said channels, an element sharply resonant to substantially the frequency of an upper harmonic generated by its associated channel and maintained in oscillation by the energy in said channel; also constituting a part of each of said channels, individual means limiting the amplitude of the oscillations maintained by its associated channel at the input terminals of said system, said means also decreasing, as said amplitude increases, the ratio between that amplitude and the amplitude of the oscillations of corresponding frequency present in its associated channel, each said individual means being actuated only by oscillations having a harmonic relationship to those maintained by its associated channel.

3. A multi-frequency oscillator, comprising: an amplifying electron tube system having an input circuit and an output circuit; a plurality of non-linear feedback channels each electrically connected to said input circuit, each, in cooperation with other parts of said oscillator, maintaining in said system continuous electrical oscillation at a single fundamental frequency, and each, by virtue of its non-linearity, generating in said system an upper harmonic of its fundamental frequency, the oscillations maintained by the several channels coexisting simultaneously and having frequencies which differ from one another; constituting a part of each of said channels, an element sharply resonant to substantially the frequency of an upper harmonic generated by its associated channel and maintained in oscillation by the energy in said channel; also constituting a part of each of said channels, individual means limiting the amplitude of the oscillations maintained by its associated channel at the output terminals of said system, said means also increasing, as said amplitude increases, the ratio between that amplitude and the amplitude of oscillations of corresponding frequency present in its associated channel, each said individual means being actuated only by oscillations having a harmonic relationship to those maintained by its associated channel.

4. A multi-frequency oscillator, comprising: a source of polarizing potential; an electron tube amplifier having an input circuit and an output circuit; a plurality of electro-mechanical non-linear feedback channels each electrically connected to said input circuit and each, in cooperation with other parts of said oscillator, maintaining in said amplifier continuous electrical oscillation at a single fundamental frequency and each, by virtue of its non-linearity, generating in said system an upper harmonic of its fundamental frequency, the oscillations maintained by the several channels coexisting simultaneously and having frequencies which differ from each other; constituting a part of each of said channels, mechanico-electric translating means actuated by energy from said output circuit and a mechanically oscillatory element sharply resonant to substantially the frequency of its associated upper harmonic, each said element being maintained in oscillation by the oscillations in its channel; and, associated with each of said channels, an individual pair of electric contacts opened and closed solely by the oscillatory element in their associated channel in response to the oscillations thereof, each said pair being electrically connected intermediate said source and their associated translating means and controlling the polarizing potential of their associated translating means only.

5. A multi-frequency oscillator, comprising: an amplifying electron-tube system having an input circuit and an output circuit; a plurality of non-linear feedback channels each electrically connected to said input circuit, each, in cooperation with other parts of said oscillator, maintaining in said system continuous electrical oscillation at a single fundamental frequency, and each, by virtue of its non-linearity, generating in said system an upper harmonic of its fundamental frequency, the oscillations maintained by the several channels coexisting simultaneously and having frequencies which differ from one another; constituting a part of each of said channels, an element sharply resonant to substantially the frequency of an upper harmonic generated by its associated channel and maintained in oscillation by the energy in said channel; also constituting a part of each of said channels, individual mechanico-electric translating and amplitude-limiting means limiting the amplitude of the oscillations maintained by its associated channel at the input terminals of said system, said means effecting such limitation by decreasing, as said amplitude increases, the ratio between that amplitude and the amplitude of mechanical oscillations present in its associated channel, each said individual means being actuated only by the mechanical oscillations present in its associated channel.

6. A multi-frequency oscillator, comprising: an amplifying electron-tube system having an input circuit and an output circuit; a plurality of non-linear feedback channels each electrically connected to said input circuit, each, in cooperation with other parts of said oscillator, maintaining in said system continuous electrical oscillation at a single fundamental frequency, and each, by virtue of its non-linearity, generating in said system an upper harmonic of its fundamental frequency, the oscillations maintained by the several channels coexisting simultaneously and having frequencies which differ from one another; constituting a part of each of said channels, a mechanically oscillatory element, and individual mechanico-electric translating and amplitude-limiting means comprising at least two electrodes of a condenser whose capacitance is periodically varied by and only by the oscillations of that oscillatory element which forms a part of its own channel, said electrodes being so shaped and so placed relative to each other that the rate of change of their mutual capacitance with respect

to the mechanical displacement of said oscillatory element is a function which decreases with increasing displacement for at least some values of said displacement.

7. The combination recited in claim 1, characterized by the fact that each said element is mechanically resonant, and by the fact that said individual means in each channel comprises an electromagnet so placed relative to that resonant element associated with it in a common channel that the mutual magnetic attraction between said electromagnet and element tends to restore said element to a position substantially midway between the extremes of oscillation.

8. A multi-frequency oscillator, comprising: an amplifying electron tube system having an input circuit and an output circuit; an electrical sound translating device in said output circuit; a plurality of non-linear feedback channels each electrically connected to said input circuit and each, in cooperation with other parts of said oscillator, maintaining in said system continuous electrical oscillation at a single fundamental frequency and each, by virtue of its non-linearity, generating in said system an upper harmonic of its fundamental frequency, the oscillations maintained by the several channels coexisting simultaneously and having frequencies which differ from each other; constituting a part of each of said channels and oscillated by acoustic energy from said translating device, an element sharply resonant to substantially harmonic relationship with the frequency maintained by the channel which comprises that element and maintained in oscillation by the harmonic current flowing in that channel; means for acoustically coupling said translating device to each of said elements; and individual means responsive to the amplitude of oscillation of each of said elements, each said individual means being adapted to vary the efficiency of coupling between its associated element and said translating device.

9. A multi-frequency oscillator, comprising: a source of supersonic polarizing potential; an electron tube system which includes an input circuit, an output circuit, a demodulator and an amplifier; a plurality of non-linear feedback channels each electrically connected to said circuit and each, in cooperation with other parts of said oscillator, maintaining in said system continuous electrical oscillation at a single fundamental frequency and each, by virtue of its non-linearity, generating in said system an upper harmonic of its fundamental frequency, the oscillations maintained by the several channels coexisting simultaneously and having frequencies which differ from each other; constituting a part of each of said channels, a sharply resonant element mechanically tuned to substantially the frequency of its associated upper harmonic; constituting a part of each of said channels, mechanico-electrical translating means, each actuated by an associated resonant element, each electrically connected to said source and to said input circuit and each modulating the supersonic potential originating at said source which is applied to said input circuit; also constituting a part of each of said channels, individual means limiting the amplitude of those oscillations in said amplifier which are maintained by the channel which comprises said means, each said individual means being actuated only by oscillations having a harmonic relationship to those maintained by that channel of which that means is a part.

10. In combination: a first source of alternating electric potential varying in accordance with a substantially constant frequency and a complex wave form; a second source of alternating potential; constituting a part of said second source, a vibratile element mechanically tuned to and strongly resonant to the frequency of one of the upper harmonics of said wave form; an electrical network operatively connecting output terminals of said first source to input terminals of said second source; constituting a part of said second source, means connected to said network and vibrating said element at substantially its natural frequency, said means for vibrating being actuated by the currents thus supplied to said input terminals; and an electrical network actuated by said second source and utilizing the electrical output of said second source.

11. In combination: a first oscillatory element mechanically resonant to a predetermined fundamental frequency; mechanico-electric translating means for electrically picking up the oscillations of said element with attendant production in its output potential of upper harmonics of said frequency; an electrical network electrically connected to said translating means; a second oscillatory element mechanically resonant to one of said harmonics; means operatively connecting said network and said second element and actuating the latter; an electrical work circuit actuated by said second oscillatory element; and mechanico-electric translating means operatively linking said second element and said circuit.

12. The combination recited in claim 10, wherein said first source comprises an oscillatory element mechanically resonant to a predetermined frequency and a non-linear resistance device actuated by the oscillations in said element and adapted to produce in the output potential of said first source harmonics of said frequency.

13. The combination recited in claim 11, wherein said first oscillatory element and said translating means comprise a source of polarizing potential and at least two electrodes of a condenser having parts operatively linked to said element and having a capacitance which is periodically varied by the oscillations of said element; in said network, electric connections between said source and said electrodes; said electrodes being relatively charged by said source of polarizing potential and being so shaped and so placed relative to each other that the capacitance of said condenser is a non-linear function of the displacement of said element.

14. In an electro-mechanical source of alternating current: an oscillatory element mechanically resonant to a predetermined frequency; electromagnetic means impressing upon said element a periodically varying component of mechanical force in time quadrature with the fundamental component of velocity of said element; and an electrical network connected to said means; in said network, means for modulating at a subaudible frequency the amplitude of said varying component, whereby the apparent natural frequency of said element is also modulated at the same subaudible frequency.

15. In an electron tube oscillator, the combination of: an oscillatory element resonant to a predetermined frequency; a regenerative electrical network actuated by the oscillations of said element and continuously maintaining said oscillations; and, electrically connected as a part of said network, means for varying at a subaudible frequency the phase angle between the oscillations delivered to said network by said

element and the oscillations delivered to said element by said network, whereby vibrato effects are producible.

16. In combination: an oscillatory element mechanically resonant to a predetermined frequency; and electromagnetic means applying to said element a periodically varying mechanical force in time quadrature with the fundamental component of velocity of said element, whereby the apparent resonant frequency of said element is altered as compared with its natural frequency in the absence of said means.

17. In an electrical musical instrument: a plurality of primary sources of electric potentials, said potentials alternating at the frequencies of a musical scale; a plurality of secondary sources of electric potentials, each of said secondary sources comprising a pair of input terminals and an element resonant to a different one of said frequencies and resonant to that one only; an electrical network having input terminals electrically connected to a plurality of said primary sources, receiving alternating potentials from a plurality of said primary sources and having output terminals electrically connected to the input terminals of said secondary sources; constituting a part of said network, an electron tube amplifier electrically connected to the input and output terminals of said network and simultaneously amplifying the output potentials of all of said primary sources; and electrically connected in said network a plurality of selectors each impressing upon the input terminals of at least one of said secondary sources an actuating potential originating at a plurality of said primary sources and characterized by a plurality of inharmonically related audio frequencies.

18. In an electrical musical instrument: a plurality of primary sources of electric potentials, said potentials alternating at the frequencies of a musical scale; a plurality of secondary sources of electric potentials, each of said secondary sources comprising a pair of input terminals and an element resonant to a different one of said frequencies and resonant to that one only; an electron tube amplifier, electric circuit connections simultaneously connecting said primary sources to said amplifier; and a plurality of electric connections each closable to connect the output terminals of said amplifier to the input terminals of a selected one of said secondary sources and to apply to said input terminals actuating potential originating at a plurality of said primary sources and characterized by a plurality of inharmonically related audio frequencies.

19. In combination: two sources of alternating electric potential; in each of said sources, an oscillatory element, both of said elements being strongly resonant to the same fundamental frequency; means for coupling together said elements, said means transmitting oscillations from one of said elements to the other, whereby the other is maintained in oscillation sympathetically with the one; and an electrical network connected to the output terminals of the source which comprises said second element.

20. In combination: an electrostatic capacitor; actuating means adapted to vary the electrostatic capacitance of said capacitor by producing relative vibratile motion between parts of said capacitor; constituting an element of said capacitor, at least one solid insulating supporting member; constituting a part of said capacitor, a pair of electrodes adapted to originate a varying electric potential by virtue of said vibratile motion; and, also constituting a part of said capacitor, a trap electrode adapted to collect and carry away leakage currents which would otherwise flow in said member from either electrode of said pair to the other.

RAYMOND C. FISHER.