

April 15, 1958

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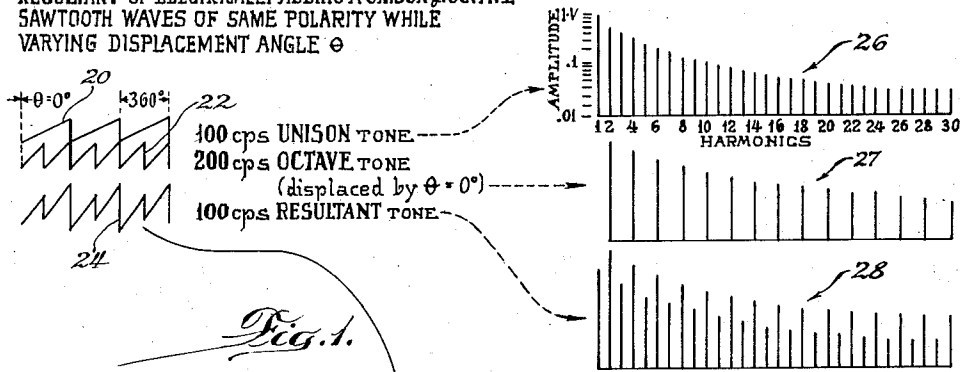
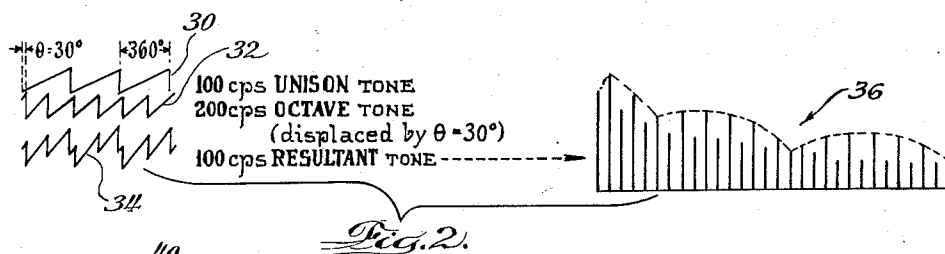
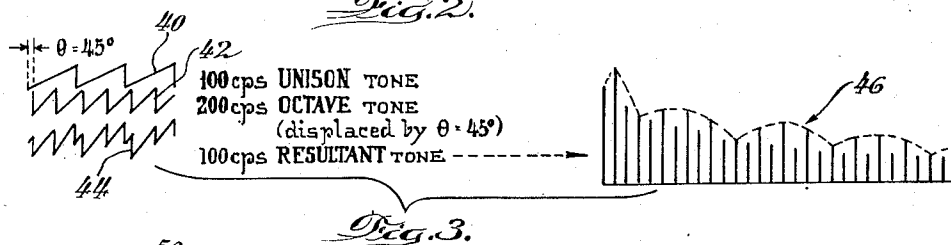
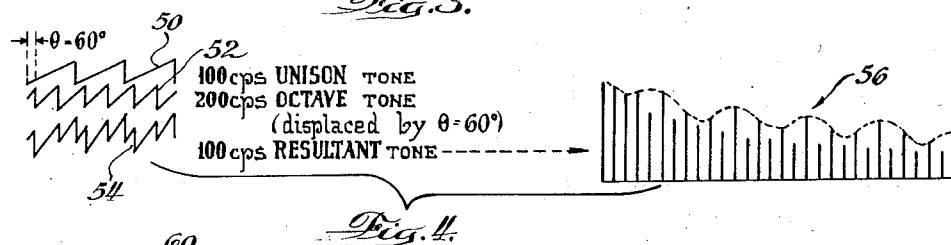
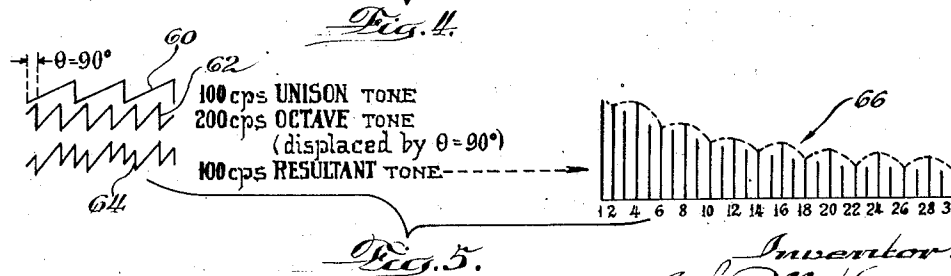
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ELECTRICAL MUSICAL INSTRUMENTS

Filed March 15, 1952

6 Sheets-Sheet 1

EXAMPLES SHOWING EFFECT ON TONE QUALITY OF
RESULTANT OF ELECTRICALLY ADDING A UNISON₂ OCTAVE
SAWTOOTH WAVES OF SAME POLARITY WHILE
VARYING DISPLACEMENT ANGLE θ



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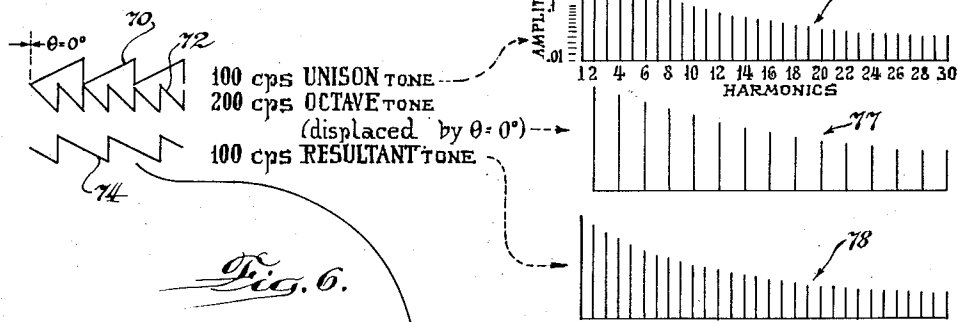
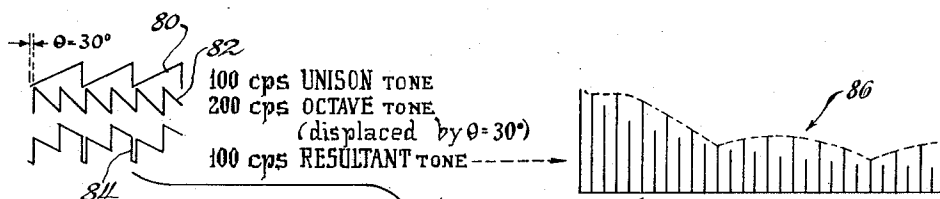
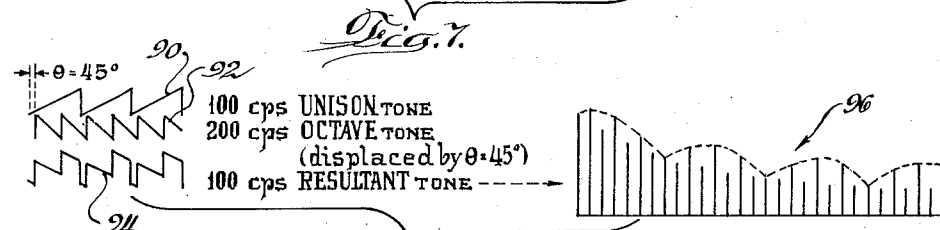
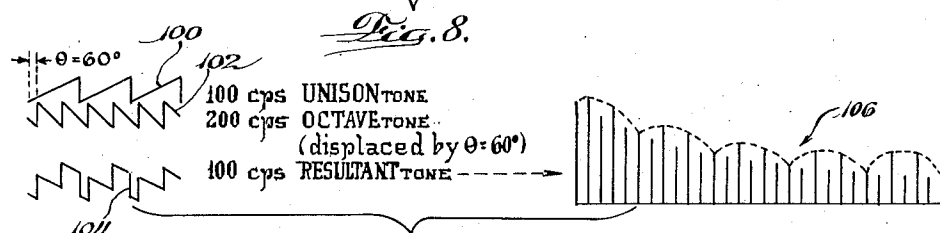
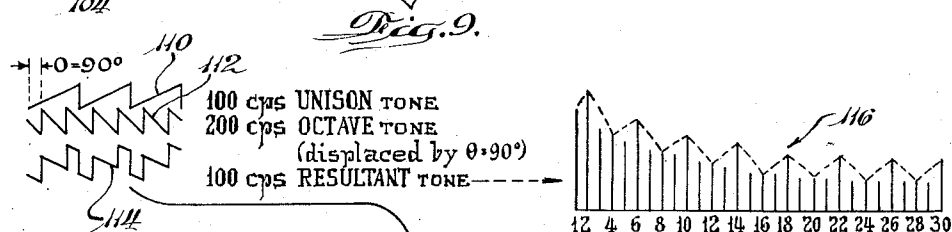
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ELECTRICAL MUSICAL INSTRUMENTS

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6 Sheets-Sheet 2

EXAMPLES UNDER SAME CIRCUMSTANCES AS FIGS. 1-5, EXCEPT THE UNISON & OCTAVE WAVES ARE OPPOSITE POLARITY.



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6 Sheets-Sheet 3

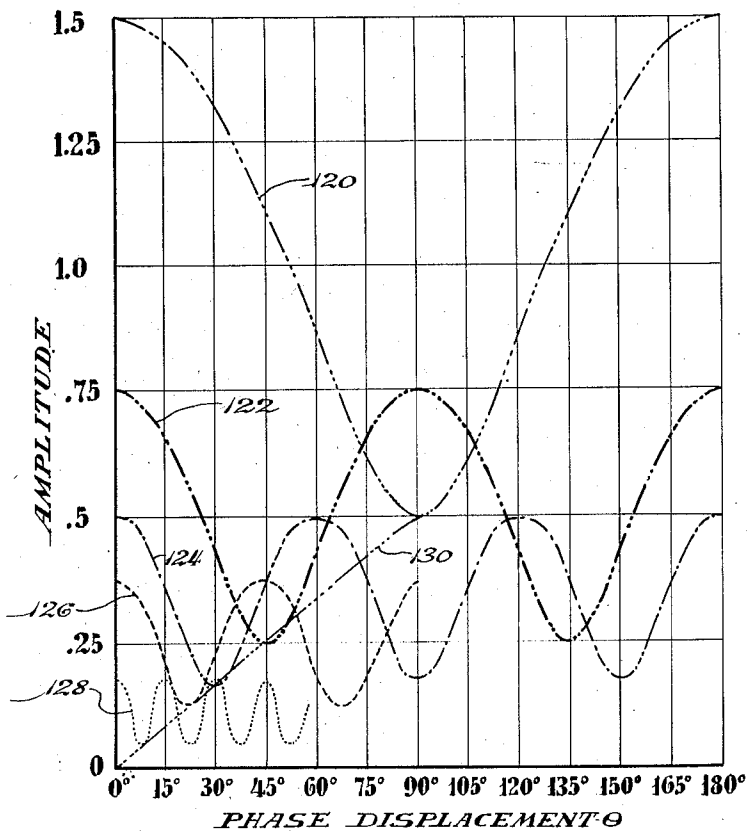


Fig. 11.

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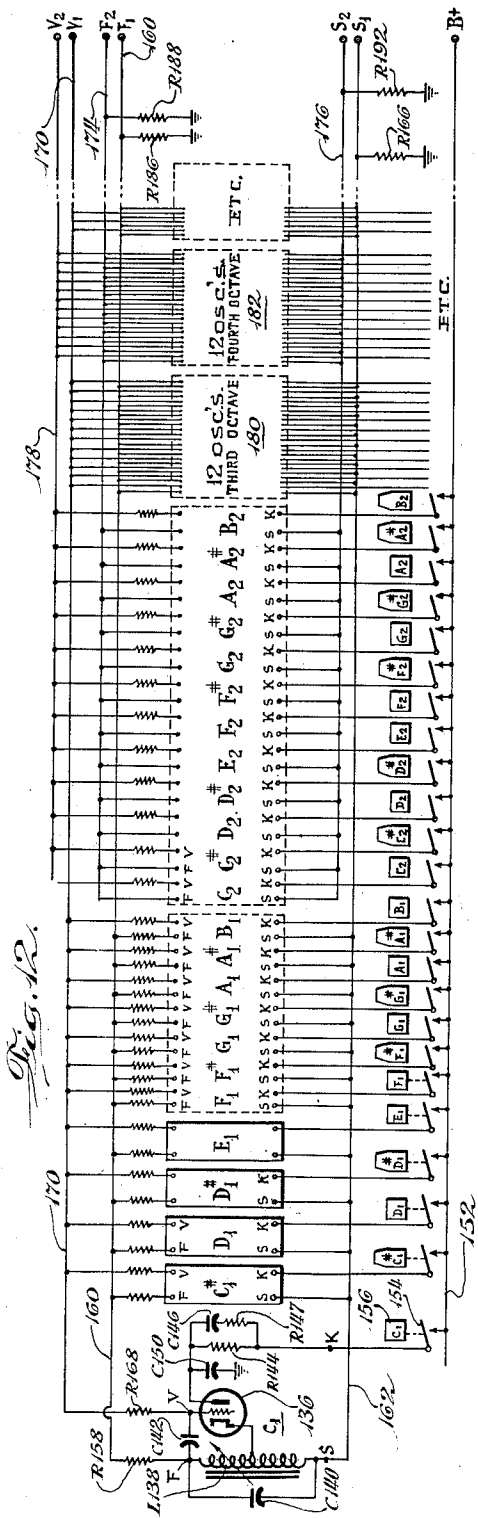
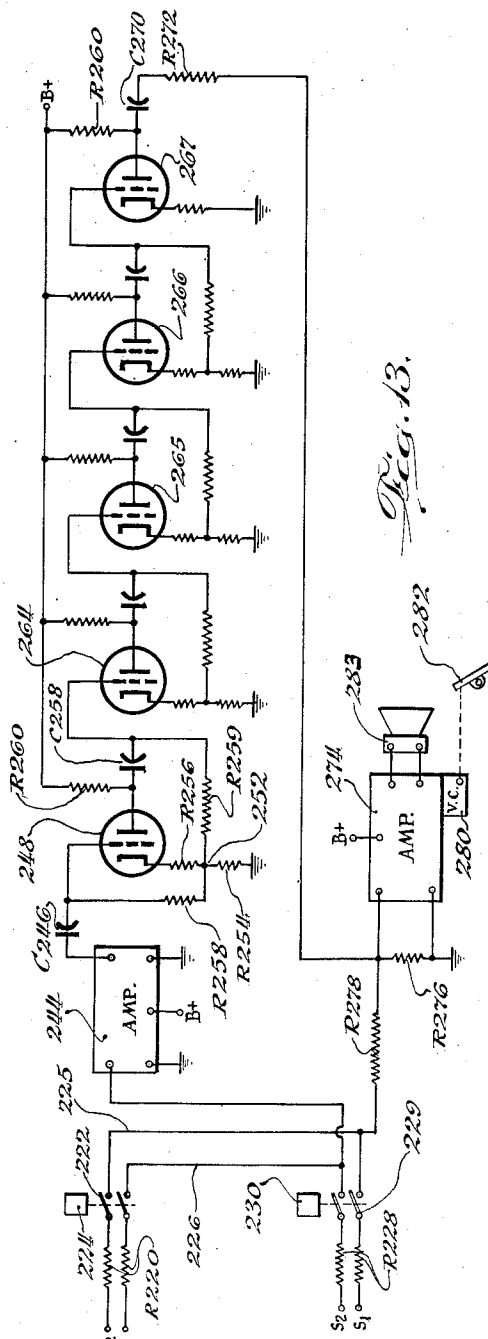
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ELECTRICAL MUSICAL INSTRUMENTS

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6 Sheets-Sheet 4



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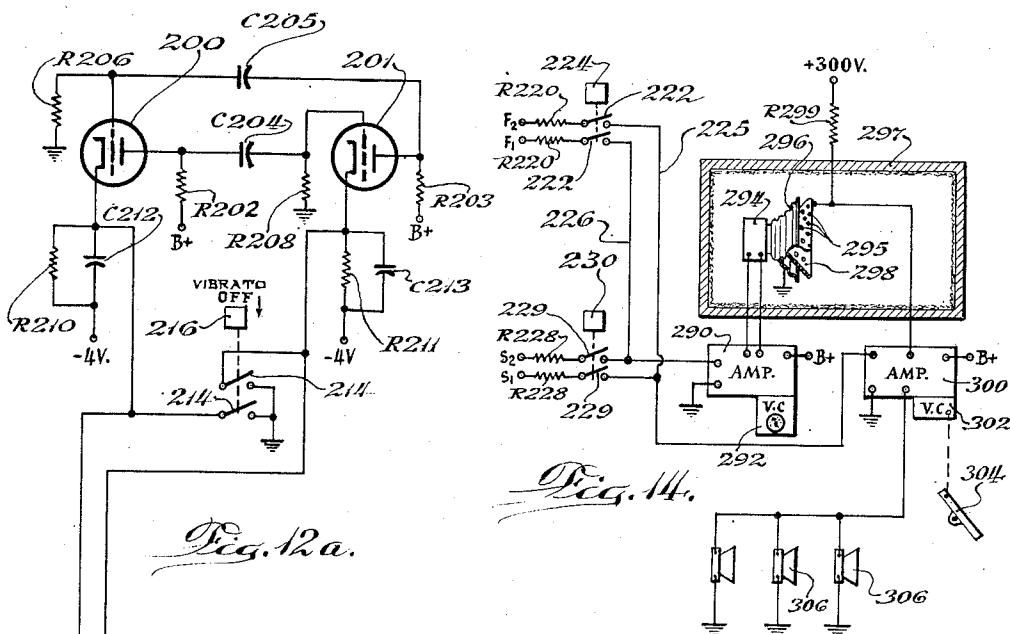
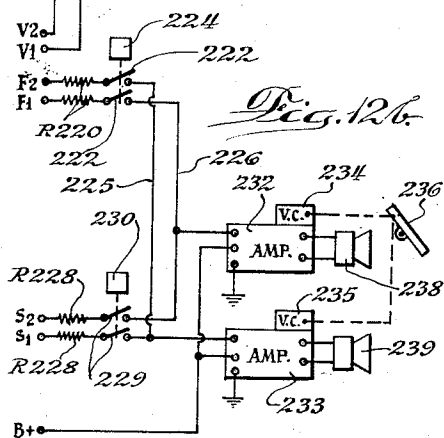
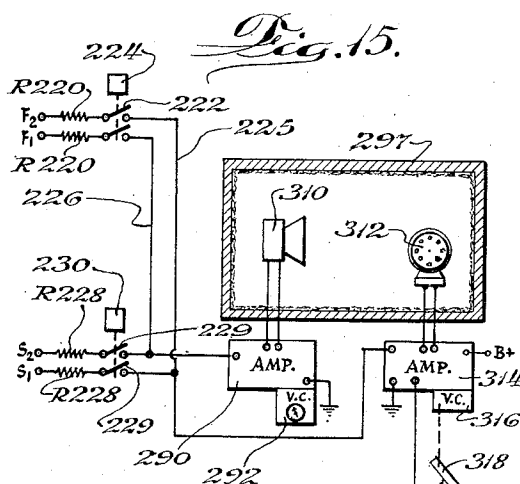
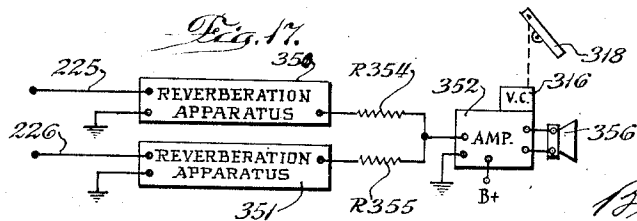
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ELECTRICAL MUSICAL INSTRUMENTS

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6 Sheets-Sheet 5



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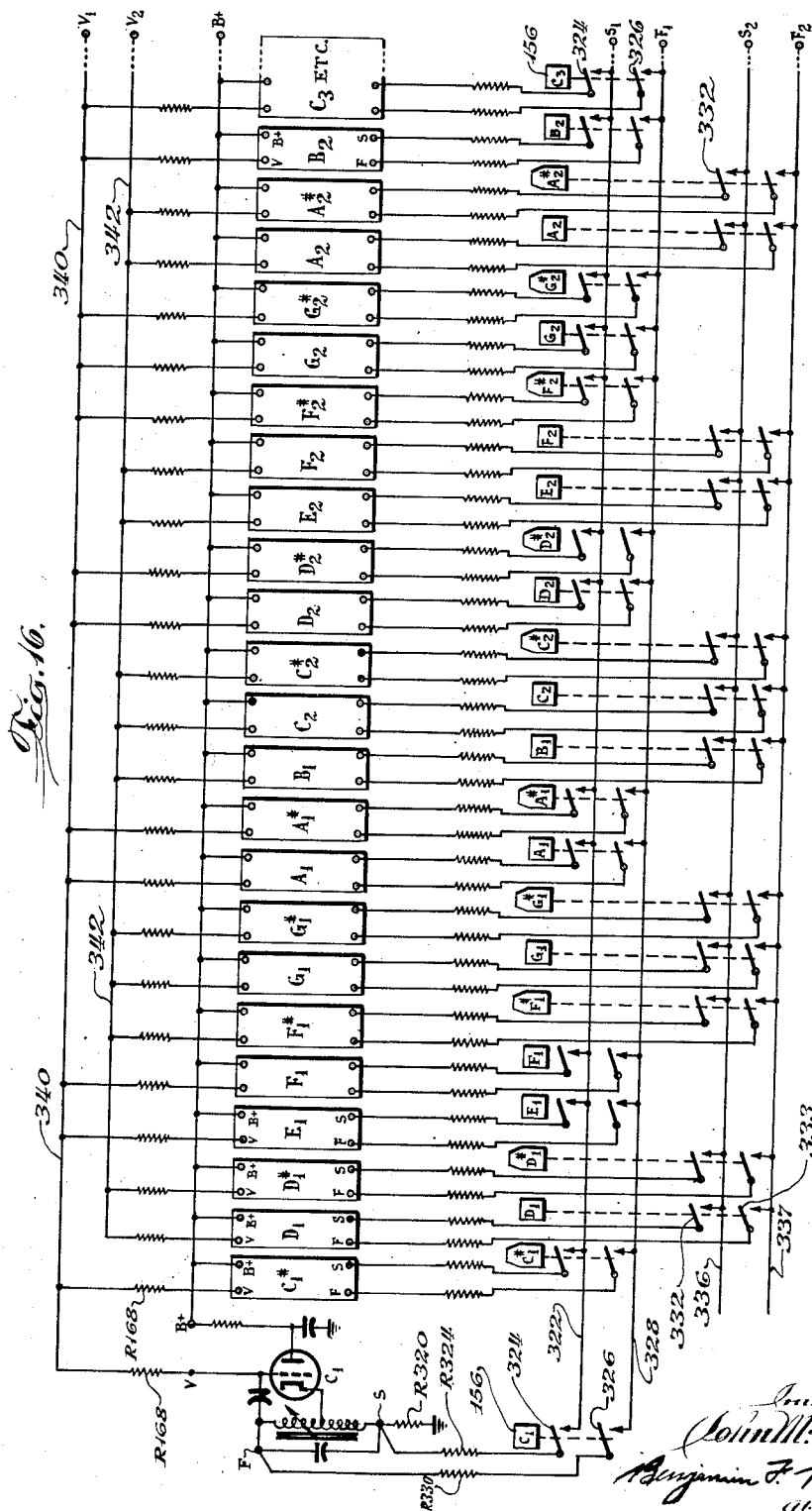
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ELECTRICAL MUSICAL INSTRUMENTS

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6 Sheets-Sheet 6



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ELECTRICAL MUSICAL INSTRUMENTS

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Application March 15, 1952, Serial No. 276,731

4 Claims. (Cl. 84—1.01)

My invention relates to polyphonic electrical musical instruments and more particularly to means and methods for improving the tone quality resulting when simultaneously sounding two octavely related tones which are harmonically complex in tone quality, each having a fundamental plus a long series of natural harmonic overtones.

A wide variety of tone generators have been proposed for producing such harmonically complex tone signals. For example, my copending prior Patent No. 2,645,968, issued July 21, 1953, shows an electronic oscillator type of generator for producing tone signals of the orchestral string family, in which the harmonically complex cathode current wave is utilized. Other oscillator systems may include auxiliary wave front distorting and rectifying elements further to increase the harmonic content. The harmonically complex wave may also be produced by generators employing rotating tone wheels, vibratory reeds, vibratory strings, sound recorded on film, magnetic wire or tape, disc, etc. While these and other similar complex tone generating techniques may be satisfactory for producing a scale of musically acceptable tones of rich quality, I have found that when two waves from octavely related generators are electrically superposed, the tone quality of the resulting octave interval usually does not have the correct quality unless some means is provided initially to "phase" the generators such that the even-numbered harmonics of the lower tone (hereinafter termed the "unison") of the octave pair are rendered in-phase and therefore additive with the corresponding frequencies in the higher pitched tone (hereinafter termed the "octave"). For example, the instant of maximum voltage generated for the second harmonic of the unison tone should occur simultaneously with the instant of maximum voltage generated for the fundamental of the octave tone. Similar considerations hold for other frequencies which are common to the two tone sources making up the octave interval, such as the fourth, sixth, and eighth harmonics of the unison tone and the second, third, and fourth harmonics respectively of the octave tone.

Generally, it is not possible, or at least not feasible, initially to "phase" the generators in this unique manner. When this is not done, I have found very objectionable variations in the tone quality when playing successive octave intervals. In fact, many of these intervals do not sound like octave intervals but merely resemble peculiar and unpredictable qualities of the unison tone having undesirable "formants" or resonant bands in their tone quality.

I have further found that when the complex tone generators take the form of independent "free-running" electrical oscillators, the "phase problem" associated with the simultaneous sounding of two generators related by the octave interval becomes particularly troublesome. For purposes of chorus tone production, it is desirable that such generators be not in exact tune so that a desirable chorus tone may be produced in the form of a "celeste" effect between the even-numbered harmonics of

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the unison generator and the fundamental and harmonics of the octave generator.

The "celeste" effect obtained by electrically superimposing the signals produced by unison and octave tone signal generators which are slightly out-of-tune with respect to each other is particularly disappointing in a tonal sense. Instead of a pleasant, steady chorus effect, one hears an unexpectedly prominent and musically undesirable "tone quality beat." These unwanted tone quality beats present themselves acoustically as cyclically varying tonal formants usually occurring slowly at a frequency which is the difference between a perfectly tuned octave (with respect to the unison) and the slightly out-of-tune octave which is used.

I have discovered that the unsatisfactory tone quality resulting from unison and octave superposition as well as the undesirable tone quality beats are caused by the geometrically simple type of wave shape which is produced inherently by practically all electrical generators capable of initially generating tone signals comprising a fundamental and long series of natural harmonic overtones. These wave shapes are characterized by a relatively few sharp wave fronts per generating cycle and simple geometric contour. A further characterization is that the number of amplitude alternations in their wave shapes per generating cycle is usually very small in comparison with the number of useful harmonic overtones contained therein. Familiar examples of wave shapes of this character are the impulse wave as generated in the cathode current of an inductance-capacity tuned electronic oscillator, or the saw-tooth wave as generated by a relaxation oscillator. Similarly, the voltage waves picked up from rotating tone wheel generators or vibrating reeds or strings usually generate their high harmonic content by employing narrow gaps between the moving and stationary elements, the latter elements being of simple non-sinusoidal shape rather than of intricate shape. Thus, a tone signal having a series of harmonics of given amplitudes, may assume a variety of wave shapes, some of which may be extremely simple in contour with but a few sudden discontinuities per generating cycle while others may be of extremely intricate contour with many alternations in amplitude per generating cycle. These generated wave shapes may be conveniently viewed with a cathode ray oscilloscope.

In order to produce electrical tone signals having simple geometric wave shapes, the phases of the various harmonics must be related to each other in a very precise and special manner. Thus, for the impulse, or sharp wave front, type of wave, all harmonics tend to have their maxima occur in a substantially additive manner at one instant only, this instant being the time at which the amplitude of the wave abruptly rises to produce the impulse wave shape. Similarly, the minima of all the partials must occur at the same instant to cause the amplitude to fall suddenly. Thus, the whole subject of sudden increase or decrease in wave amplitude may be viewed as being caused by groups of closely related harmonics having their instants of maximum or minimum amplitude occur simultaneously or nearly simultaneously. As the number of harmonics which are relatively phased for simultaneity of maximum or minimum amplitude becomes greater, the number of alternations in amplitude per generating cycle becomes less and the resulting wave shape tends to become more simple in contour.

This being the case, it may be stated that groups of adjacent even-numbered harmonics of the unison are usually correlated in phase in such a manner that when a similar wave at the octave is superimposed thereon these closely related even harmonics of the unison tend either to add to or to cancel the corresponding frequencies in

the octave, to produce formants or bands of harmonic prominence in the octave interval tone. For example, if the phase between the unison and octave waves is such that the tenth harmonic of the unison wave is additive with the fifth harmonic of the octave wave, it will be found that the eighth and twelfth harmonics of the unison impulse wave are also likely to be additive at the same instant with the corresponding fourth and sixth harmonics of the octave impulse wave. This concurrence of harmonic reinforcement or cancellation by closely corresponding harmonic frequencies in the unison and octave signals is the basic phenomenon which is productive of the peculiar "formants" in the octave tone qualities as well as the undesirable "tone quality beats" as heard when playing the octave interval from sources which are not perfectly in tune.

In the specification and drawings which follow, it will be shown that the electrical superposition of the output signals of unison and octave generators does produce very distinct recurring reinforcements for various bands of harmonic frequencies corresponding to various relative phases between the unison and octave waves. It will further be shown that when the unison and octave waves are slightly out of tune with respect to each other, the relative phases of their partials are continually changing, which results in corresponding shifts in the audio frequency zones or bands of harmonic reinforcement and cancellation—which may be complete or partial. These shifting zones of harmonic reinforcement between the even-numbered harmonics of the unison and the fundamental and harmonics of the octave produce the variable tone quality formants perceived by the listener as the unwanted "tone quality beats."

With the apparatus of my invention, this inherent generator phasing problem is obviated, and the tonal output obtained by superimposing the outputs of octavely-related complex generators of any type or construction is substantially free from objectionable formants or "tone-quality beats," regardless of the shapes of the waves, their relative phase, or whether the generators are exactly in tune.

It is the primary object of my invention to provide a novel method and apparatus for obviating these basic superposition problems, and to provide for musically acceptable superpositions on all octave intervals, as well as to eliminate "tone quality beats."

A further object is to provide various improved means for eliminating or greatly reducing tone quality beats.

Other objects will appear from the following description, reference being had to the accompanying drawings in which:

Figure 1 shows a group of saw-tooth waves and a resultant wave together with charts of their harmonic analyses, to illustrate the effects of electrically adding unison and octave saw-tooth waves of the same polarity and in the same phase (that is their relative phase angle θ is 0°);

Figure 2 shows a similar set of saw-tooth waves of unison and octave pitch with the resultant wave form, and a chart showing the harmonic analysis of the resultant, when the octave wave is displaced from the unison wave by a phase angle θ of 30° ;

Figure 3 is a set of wave forms and a harmonic analysis chart similar to Fig. 2 when the phase angle difference θ is 45° ;

Figure 4 is a set of wave forms and a harmonic analysis chart similar to that shown in Fig. 2 when the difference in phase θ between the two waves is 60° ;

Figure 5 is a group of wave forms and a harmonic analysis chart similar to Fig. 2 when the difference in phase θ between the two waves is 90° ;

Figure 6 shows wave forms for unison and octave saw-tooth tone signals together with a chart showing the harmonic analyses thereof when the unison and octave waves are of opposite polarity and in the same phase ($\theta=0^\circ$);

Figure 7 shows the wave forms of unison and octavely

related saw-tooth waves and the resultant wave together with a chart showing the harmonic analysis of the latter, when the waves are displaced in phase θ by 30° ;

Figures 8, 9, and 10 show the wave forms of the unison and octave interval saw-tooth wave forms and their resultant wave forms together with charts illustrating the harmonic analyses of the resultant waves, when the saw-tooth waves are of opposite polarity and displaced by phase angles θ of 45° , 60° , and 90° respectively;

Figure 11 is a graph showing how the amplitudes of the resultants of partials of a unison tone and correspondingly pitched partials of an octavely related tone, both of saw-tooth wave shape, change as the phase angle θ between the two waves is changed;

Figure 12 is partly a block and partly a schematic wiring diagram of the tone signal generating and collecting portion of an electrical musical instrument incorporating the invention;

Figure 12a is a schematic wiring diagram of an oscillator for generating a vibrato frequency signal for modulating the signals produced by the generators shown in Fig. 12;

Figure 12b discloses an output system suitable for connection to the output terminals of the generating system shown in Fig. 12;

Figure 13 is a schematic wiring and block diagram of a modified form of output system designed to be coupled to the output terminals of the generating system shown in Fig. 12;

Figure 14 is a schematic and diagrammatic illustration of a third form of output system which may be utilized with the generating system of Figs. 12 and 12a;

Figure 15 is a schematic and diagrammatic view of a fourth form of output system which may be used with the generating system of Figs. 12 and 12a;

Figure 16 is a schematic wiring and block diagram of a form of tone signal generating system which may be used in place of that shown in Fig. 12; and

Figure 17 is a block and schematic wiring diagram of a fifth form of output system which may be used with the generating system shown in Figs. 12 and 12a or with that shown in Fig. 16.

In Fig. 1 there is illustrated a unison saw-tooth tone signal wave 20, and a similar wave 22 one octave higher in pitch, together with a wave 24 which represents the resultant wave when the waves 20 and 22 are electrically superimposed in a circuit. The waves 20 and 22 are of the same polarity and are in phase ($\theta=0^\circ$). There is also included a chart 26 illustrating the results of a harmonic analysis of the saw-tooth wave 20, a chart 27 illustrating the harmonic analysis of the saw-tooth wave 22, and a chart 28 showing the harmonic analysis of the resultant wave 24.

It will be noted that in the charts 26, 27, and 28 the ordinates are drawn to a logarithmic scale and that the fundamental frequency is, in each instance, assumed to have an amplitude of unity, indicated as one volt (1 v.). The second harmonic of the chart 26 adds to the fundamental of the octave shown in chart 27, so that in the resultant the second harmonic is of a greater amplitude than the fundamental.

It is well known that a saw-tooth wave having a fundamental frequency (f) of unit amplitude contains harmonics of the Fourier series: $\frac{1}{2}$ ($2f$), $\frac{1}{3}$ ($3f$), $\frac{1}{4}$ ($4f$) . . . It will be noted that the second harmonic in the resultant tone shown in chart 28 has an amplitude 1.5 times that of its fundamental. Similarly all of the even-numbered harmonics in the resultant wave 24 have amplitudes substantially greater than the adjacent odd-numbered harmonics. The tone heard when the wave 24 is translated into sound will therefore be perceived as a satisfactory octave interval effect because of the addition of all even-numbered harmonics of the unison with the fundamental and harmonics of the octave.

However, if the unison and octave waves are not in

phase (θ is not equal to 0°), different results occur. For example, in Fig. 2 the unison wave 30 is displaced from the octave wave 32 by a phase angle θ of 30° , and the resultant wave 34, occurring when waves 30 and 32 are electrically superimposed, has a shape radically different from that of the wave 24.

A harmonic analysis of the wave 34 is shown in chart 36. It will be understood that in the charts indicating the harmonic analysis of the tone qualities the vertical lines represent amplitude only and do not indicate in any way the relative phases of the partials. From the chart 36 it will be noted that the odd-numbered harmonics progressively decrease in amplitude with increasing frequency according to the above noted Fourier series, but that the even-numbered harmonics vary in amplitude in an entirely different manner, as though they had been passed through a series of resonant channels (or tone "formants"). Some of the even harmonics are attenuated substantially as compared with the chart 28 which represents the harmonic analysis when the unison and octave tone signals are superimposed with no phase displacement. The quality of the tone produced by the signal having the form of the wave 34 obviously differs from that of the wave 24.

In Fig. 3 a unison signal wave 40 and its octave signal wave 42, displaced by a phase angle of 45° , are shown together with the resultant wave 44 which would be formed by electrically superimposing the waves 40 and 42. The chart 46 illustrates a harmonic analysis of the wave 44 from which it is apparent that while the odd harmonics taper off in the normal manner, in accordance with the Fourier series, many of the even harmonics are attenuated considerably, as if they had been transmitted through a series of resonant channels (or tone "formants"). The quality of the tone produced by the signal wave 44, when translated into sound, differs materially from that produced by the translation of the signal wave 24 into sound. This difference in tone quality is due solely to the 45° phase displacement of the unison and octave waves 40 and 42. Likewise, wave 44 differs from wave 34 because the zones of harmonic reinforcement occur at different and more closely related frequencies.

In Fig. 4 the unison signal wave 50 is combined with the octave signal wave 52, displaced by a phase angle of 60° , to produce a resultant wave 54 which has a harmonic analysis shown by the chart 56. It is readily apparent how this phase displacement affects the quality of the tone produced by the resultant wave. Comparing the chart 56 with the chart 28, it would appear as if the even-numbered harmonics of chart 56 had been passed through five or six resonant channels for the 30 harmonics shown. The quality of the tone represented by the chart 56 obviously differs substantially from those represented by the charts 28, 36, and 46.

In Fig. 5 the unison tone signal wave 60 and an octave wave 62, displaced by a phase angle of 90° , are electrically superimposed to produce a resultant wave 64. The harmonic analysis of the resultant wave 64 is shown by a chart 66 in which the odd harmonics are uniformly decreasing in amplitude with increase in frequency, whereas the second, sixth, tenth, fourteenth, etc. harmonics are substantially attenuated so as to have amplitudes approximately the same as those shown in the chart 26. The quality of the tone represented by the chart 66 is quite apparently different from the quality represented by the chart 28 and also differs substantially from the tone qualities represented by the charts 36, 46, and 56.

If, as illustrated in Fig. 6, a unison wave 70 is combined with an octave wave 72 of opposite polarity but in phase ($\theta=0^\circ$), the resultant wave 74 will be produced. The unison saw-tooth wave 70 has a harmonic analysis indicated by the chart 76, its octave saw-tooth wave 72 has its harmonic analysis represented by the chart 77, while the resultant wave 74 has its harmonic analysis

indicated by the chart 78. Since the second harmonic in the chart 76 has an amplitude of .5 v., whereas the fundamental of chart 77 has an amplitude of 1.0 v., and since these sine waves are of opposite phase, the resultant wave shown in chart 78 will have an amplitude of .5 v. By similar reasoning it will be clear that the charts 76 and 78 must be identical, and, surprisingly, the electrical superposition of the octave wave 72 on the unison wave 70 had no effect whatsoever in changing the tone quality. This is probably the most undesirable condition that may occur, because, if the generators of the waves 70 and 72 remain in the same relative phase, it is clearly apparent that a musician playing the unison key and thereafter pressing the octave key would hear no change or addition whatsoever. This defect is also made apparent by a comparison of waves 70 and 74. Both are saw-tooth waves of the same frequency and amplitude and differ only in that they are of opposite polarity and displaced 180° in phase, and therefore sound identically.

Figure 7 illustrates the wave shapes and the harmonic analysis of the resultant tone signal upon superposition of a unison wave 80 upon an octave wave 82 of opposite polarity displaced by a phase angle θ of 30° . The resultant wave 84 has a harmonic analysis indicated by the chart 86. Again it will be noted that various even harmonics are substantially attenuated whereas the odd harmonics decrease in amplitude in the expected manner. This chart has the appearance as if the even harmonics only in the resultant chart 86 had been passed through several resonant channels of different frequency ranges. The quality of the tone represented by the chart 86 is, of course, decidedly different from that represented by the chart 28, further illustrating that the polarity and relative phases of the unison and octave tone signals have a substantial effect upon the resultant wave shape and tone quality.

Figure 8 shows how a unison wave 90 displaced 45° from an octave wave 92 of opposite polarity electrically superimposed thereon will produce a wave 94 having a harmonic analysis represented by the chart 96. This harmonic analysis is one which would be expected if the even harmonics only had been passed through four resonant channels of different frequency attenuating characteristics.

Figure 9 illustrates how a unison wave 100, combined with an oppositely polarized octave wave 102, displaced by an angle of 60° , produces a resultant wave 104 having a harmonic analysis represented by the chart 106. One would expect the harmonic analysis represented by the chart 106 to have resulted from passing the even harmonics only through five different "formant" channels while the odd harmonics were transmitted through a linear system.

In Fig. 10 a unison wave 110 is shown together with its oppositely polarized octave wave 112, displaced by 90° to produce a resultant wave 114. The resultant wave has a harmonic analysis represented by the chart 116 showing how alternate even harmonics are attenuated to an extent that, with respect to these particular harmonics, the addition of the octave tone had no effect.

From the waves and charts shown in Figs. 1 to 10 it is clear that the relative polarity of the unison and octave signals, and their relative phase displacements, have pronounced effects upon the tone quality when the octave and the unison are sounded simultaneously. Moreover, when two nominally octavely related, harmonically complex tone signals of simple wave form are electrically superimposed and are of changing relative phase (as is necessarily true if they are not of exactly octavely related frequencies) the quality of the resultant wave translated into sound will be continuously changing, resulting in what has heretofore been termed a "tone quality beat." This beat is musically undesirable and is very annoying to the musically trained ear and, as previously

stated, it is one of the primary objects to provide a musical instrument in which this effect will not occur.

This undesirable effect is further illustrated by the chart shown in Fig. 11. In this chart the curve 120 represents the resultant amplitude, at different phase displacements θ , of the fundamental of the octave wave and the second harmonic of the unison wave, both waves being of saw-tooth shape and having unity fundamental amplitude. The amplitudes in this chart are plotted on a linear scale. It will be observed that the curve 120 drops from a value of 1.5 when these partials are in phase to a value of .5 when their phase displacement θ is 90° .

The curve 122 shows the amplitude of the resultant of the fourth harmonic of the unison and the second harmonic of the octave when these partials are in various phase difference relationship. It will be noted that when the phase displacement θ is 0° the resultant of these partials has an amplitude of .75, whereas when θ is 45° the resultant has a value of .25.

Curve 124 represents the amplitude of the resultant of the third harmonic of the octave and the sixth harmonic of the unison showing that there is a variation in amplitude of from .5 to .167 when the phase angle θ changes from 0° to 30° .

Curve 126 represents the amplitude of the resultant of the fourth harmonic of the octave with the eighth harmonic of the unison, showing that the amplitude of the resultant of these partials changes from .375 to .125 as the phase difference between these partials changes from 0° to 22.5° .

The curve 128 illustrates the amplitude of the resultant of the twelfth harmonic of the octave with the twenty-fourth harmonic of the unison. As the phase angle between these partials changes from 0° to $7\frac{1}{2}^\circ$ the amplitude of their resultant changes from .1875 to .0625.

In the aggregate, the curves of Fig. 11 show the relative importance of maintaining the partials of two octave-related tone signals which are sounded simultaneously in the same phase relation if the signals are to be electrically superimposed. The chart shows that with octave-related tones the phase relationship between the fundamental of the octave and the second harmonic of the unison is of most importance. The second most important phase relationship is that between the second harmonic of the octave and the fourth harmonic of the unison. Of third importance, as indicated by the curve 124, is the phase relationship of the third harmonic of the octave and the sixth harmonic of the unison. The relationship of the other harmonics of the octave and unison tones which are of the same nominal pitch becomes of progressively less importance as indicated by the curves 126 and 128.

The locus of the low amplitude points of the curves 120, 122, 124, 126, and 128 lie in a straight line shown as the dotted line 130 in Fig. 11 which clearly indicates the expected fact that the out-of-phase relationship of higher order partials of the unison and octave tone signals, which are of the same nominal pitch, becomes progressively less important in characterizing the musical tone quality.

One way in which the undesirable effects pointed out with reference to the charts and waves of Figs. 2 to 10 may be avoided for all practical purposes is illustrated in Fig. 12 which shows representative portions of a tone signal generating system for an electronic organ or other similar polyphonic electrical musical instrument. In this instrument there is an electronic oscillator for providing a signal for each semitone pitch within the gamut of the instrument. These oscillators may be of any desirable construction and the oscillator for the note C1 of Fig. 12 is illustrated as one suitable for this purpose.

The oscillator comprises a triode 136 having a resonant circuit comprising a variable inductance L138 and a capacitor C140 connected in parallel between terminals F and S. The terminal F is connected to the control

grid of the triode and to a terminal V through a capacitor C142. The cathode of the triode 136 is connected to a tap on the inductance L138 while the plate of this triode is connected to a terminal K through a resistor R144, the latter having a capacitor C146 with a resistor R147 in series connected across it. The plate is also connected to ground through a capacitor C150. The terminal K is adapted to be connected to a busbar 152 upon closure of a switch 154 operated by a playing key 156.

A flute-like tone signal of substantially sine wave form is derived from the F terminal through a decoupling resistor R158 and a collector conductor 160 which leads to an output terminal F1 of the generating system. A complex tone signal, representative of a string tone, is derived from the terminal S of the oscillator and is impressed upon a collector conductor 162 which leads to a terminal S1 of the generating system and is connected to ground through a resistor R166. The V terminal of the oscillator C1 is connected by decoupling resistor R168 to a conductor 170 which is connected to a terminal V1.

When the switch 154 is closed by the operation of its playing key 156, plate current is supplied to the oscillator C1 through the resistor R147 and capacitor C146 to produce an initial surge of plate current and thereafter is continuously supplied through the resistor R144 which, together with the capacitor C150, constitutes a means for causing the oscillator to commence operating with a sufficiently gradual attack to be devoid of undesirable transients.

The other oscillators of the lowest octave, namely, the oscillators C#1 to B1, have their F, S, and V terminals connected to the conductors 160, 162, and 170 in the same manner as the oscillator C1. However, the oscillators for the second lowest octave, namely, the oscillators C2 to B2, have their F terminals connected to a conductor 174 which leads to an output terminal F2 of the generating system while their S terminals are connected to a conductor 176 leading to an S2 output terminal of the generating system. The V terminals of these oscillators are connected to a conductor 178 leading to a V2 terminal of the generating system.

The oscillator group 180 for the third octave are connected in the same manner as the oscillators for the lowest octave, namely, the C1 to B1 oscillators, whereas the twelve oscillators constituting the fourth octave, represented by the block 182, having their F, V, and S terminals connected in the same manner as those of the second octave, namely, C2 to B2. In a similar manner any additional octaves of oscillators within the gamut of the instrument will alternately have their F, S, and V terminals connected in the same manner as the lowest octave and the second lowest octave of oscillators. It will be noted that the conductor 160 is connected to ground through a load resistor R186, while the conductor 174 is similarly connected to ground through a load resistor R188. The conductor 176 is connected to ground through resistor R192 while, as previously indicated, the conductor 152 is connected to a suitable source of plate current indicated as a B+ terminal.

The terminals V1 and V2 have signals of the same vibrato frequency but of opposite phase impressed thereon through an apparatus shown in Fig. 12a, which comprises an oscillator having triodes 200 and 201. The plate of triode 200 is connected to a source of plate current represented by a terminal B+ through a resistor R202 and is connected to the grid of triode 201 through a capacitor C204. In a similar manner the plate of the triode 201 is connected to a B+ terminal through a resistor R203 and is connected to the grid of triode 200 through a capacitor C205. The grids of triodes 200 and 201 are respectively connected to ground through grid resistors R206 and R208 while their cathodes are connected to a -4 v. terminal of the power supply

through resistances R210 and R211, respectively, the latter being provided with by-pass capacitors C212 and C213. The cathodes of the triodes 200 and 201 are adapted to be connected to ground upon closure of switches 214, operable by a suitable tablet 216, whenever the vibrato effect is not desired.

The output system of the instrument is shown in Fig. 12b, in which the terminals F1, F2, S, S2 and B+ correspond to the similarly designated terminals of Fig. 12. Resistors R220 connect terminals F1 and F2 to poles of single-throw switches 222 operated by a suitable stop tablet 224, the other poles of these switches being respectively connected to conductors 225 and 226. In a similar manner terminals S2 and S1 are connected by decoupling resistors R228 to switches 229 operated by a stop tablet 230, switches 229 connecting the terminals S1 and S2 to the conductors 225 and 226 respectively.

The conductors 225 and 226 form part of input leads for a pair of amplifiers 232 and 233, the other input leads for these amplifiers being represented as a ground connection. The amplifiers have volume controls 234, 235 associated therewith operable by a common control indicated as a swell shoe 236. The outputs of the amplifiers 232 and 233 are supplied to speakers 238 and 239 respectively.

The instrument shown in Figs. 12, 12a, and 12b, it will have been noted, has its connections so made that signals from oscillators of alternate octaves will be amplified and converted into sound by the amplifier 232 and speaker 238 while the signals from oscillators of the intermediate octaves will be supplied to amplifier 233 and translated into sound by speaker 239. In this way, the phase shifting effects produced by the speaker cone are applied to the unison and octave waves separately before they are acoustically superimposed and finally reach a listener's ears. Violent changes in the wave forms are produced before they reach the listener's ears because a loud speaker cone does not vibrate as a "piston" (except for the low bass frequencies) but rather breaks up into a very complicated vibration pattern which will cause relative phase shifts among the harmonics on a substantially random basis. The simple geometric shape of wave as initially generated is thus completely destroyed and all co-relation between the instants of maxima and minima for the various harmonics are removed. A microphone connected to an oscillograph would show the shape of wave to be much more intricate in its contour with the occurrence of many alternations in amplitude in each cycle. If such an acoustically modified unison wave is superimposed on an octave wave, the well known square root law of random superposition holds, and like harmonic frequencies in the unison and octave components tend to be additive in a statistical sense. For example, two harmonics of corresponding frequency, each of unit energy, randomly superimposed will most likely combine to produce a signal the energy of which is the $\sqrt{2}$ or approximately 1.4 times the energy of one of the sources. However, the energy of the combined signal may lie anywhere from zero to twice the energy of one of the sources.

Under the above described circumstances, it becomes substantially impossible for adjacent bands of even-numbered harmonics of the unison to combine in a like manner to add or cancel with the corresponding frequencies in the octave to produce unwanted tone quality formants in the resultant octave interval tone.

From the above it will be apparent that the statistical addition of unison and octave waves, in all probability, will not result in exactly the octave quality which can occur only if the even-numbered harmonics of the unison and those of corresponding frequency in the octave are combined with exact in-phase relationships. The amplitude irregularities produced in the resultant octave interval tone, however, make it highly superior in an

artistic sense to perfect in-phase superposition because the various octave intervals, while sounding very much alike in a general tone quality sense, are nevertheless entirely different in their exact harmonic analysis, that is, if each harmonic component is individually considered. For example, the resultant tone of one octave interval may have strong 20th and 24th harmonics but weak 22nd and 26th harmonics. In both cases the total high harmonic content may compare closely but the exact harmonic series be entirely different. I have discovered that in hearing, the ear does not function to evaluate the amplitude of each individual harmonic but rather ascribes a general loudness or tonal brilliance to bands of harmonic frequencies. If two octave intervals have bands which are of comparable acoustic energy the ear will notice no objectionable difference in quality. Nevertheless, as one plays successive octave intervals up the keyboard a highly desirable freedom from tonal monotony (which is produced with perfectly controlled in-phase harmonic addition) is avoided and a very superior and artistic tonal result is thereby achieved.

When the unison and octave components are not exactly in tune with each other, the phenomena of superposition becomes highly intricate in which the various pairs of corresponding harmonic frequencies in the unison and octave waves beat in and out of phase at instants of time which are in no way co-related. For example, reinforcement of the second harmonic of the unison with the fundamental of the octave will probably not occur at the same instant as the fourth harmonic of the unison reinforcing with the second harmonic of the octave. Furthermore, as the beat rates of corresponding pairs of harmonics occur at differing rates, the overall superposition phenomena can contain no single objectionable beat rate. The chorus effect is then perfectly smooth without the presence of any unwanted tone quality beats.

It will be also noted that alternate octaves are connected to vibrato signals at one phase while intermediate octaves of oscillators are connected to the vibrato terminal at which the signal is of opposite phase. This further enhances the quality of the tones heard because as the frequency representing the second harmonic of the unison note is going sharp the fundamental of the octave will be going in the flat direction and a highly desirable vibrato chorus effect will result. This feature per se is not claimed herein.

In some instances, especially when high volume acoustic output is required, it may be desirable to employ a single output system of the type illustrated in Fig. 13 in place of that shown in Fig. 12b. As in the case of the output system of Fig. 12a, that of Fig. 13 is connected to the terminals F1, F2, S1, S2, and B+ in the same manner, and the same reference characters have therefore been applied to the corresponding parts. In Fig. 13 the signals from the S2 terminal and the F1 terminal are supplied through conductor 226 and ground to the input terminals of preamplifier 244, one of the output terminals of which is connected to ground while the other output terminal is connected through a capacitor C246 to the grid of a triode 248 forming the first stage of a phase shifting network. This triode is provided with a grid resistor R250 coupled to a junction point 252 which is connected to ground through a resistor R254. This junction is also connected to the cathode of the triode 248 by a resistor R256. The plate of the triode 248 is coupled through a capacitor C258 with a second stage of the phase shifting network and is supplied with plate current through a load resistor R260 connected to the B+ terminal of the power supply. The cathode of triode 248 is also coupled to the input of triode 264 by resistor R259. The second stage includes a triode 264, and similar successive sections include triodes 265, 266, and 267. This phase shifting network changes the sharply peaked pulse type input waves to an irregularly shaped wave which crosses the zero axis a

large number of times during each cycle, due to the differing time delay afforded for the various harmonics imparted by the phase shifting network.

By making the impedances of the capacitors equal to the impedances of the resistors at a low frequency relative to the fundamental, the circuits function in a manner similar to a high pass filter insofar as wave form distortion is concerned. This has the added advantages that expensive coils are not required and that the output frequency response characteristic is essentially flat over the entire audio frequency spectrum and has no cut-off effect as would be present with a high pass filter.

The plate of the last triode 267 of this network is coupled through a blocking capacitor C270 and a decoupling resistor R272 with one of the input terminals of a power amplifier 274. A resistor R276 is connected between said terminal of the power amplifier and ground and such terminal is also connected to the conductor 225 through a decoupling resistor R278. The values of the components of the two channels are such that signals therefrom impressed upon the input of amplifier 275 are of substantially the same amplitude.

The power amplifier 274 has a volume control device 280 associated therewith, this device being operable by the expression or swell shoe 282 of the instrument. The output of the amplifier is coupled to one or more speakers 283. In this embodiment of the invention, the wave form distorting characteristics of the resistance-capacitance networks are effective to render the wave of one of the octave interval components considerably more intricate in shape than was originally generated. When this more intricate shape of wave is combined with the octave interval component, the superposition becomes correspondingly more intricate, in which adjacent groups of even-numbered harmonics in the octave interval wave are very much less likely to combine in a similar manner with each other to produce unwanted formants. When the unison and octave components are not exactly in tune with each other, the resulting superposition becomes still more intricate, with the various pairs of corresponding frequencies in the unison and octave waves going into and out of phase at differing instants of time. The chorus effect produced is smoother and unwanted tone quality beats are reduced. While the wave form distortion network is effective to produce a considerable degree of intricacy in the output wave, it is, in general, not as effective as are the separate amplifiers and speakers wherein substantially random phases are produced among the harmonics. By increasing the number of sections of the network, the number of alternations in amplitude per cycle are increased and the unison and octave superposition is correspondingly more satisfactory. The principal advantage of this form of the invention is that but one power amplifier is required.

A further modification of the output system which may be used with the generating system of Figs. 12 and 12a is shown in Fig. 14. The input circuit parts which are similar to those of Fig. 12b bear corresponding reference characters. The conductor 226 is connected to one input terminal of an amplifier 290, the other input terminal being connected to ground. The amplifier 290 is provided with a manually set volume control 292 and its output is connected to a specially constructed speaker 294. This speaker is contained in a room or box 297 having acoustically "dead" inner walls of suitable sound-absorbent material. The inner surface of the cone 298 of the speaker is coated with a conductive paint, as by the application of a solution of colloidal graphite, and this inner surface is connected to ground. In closely spaced relation to the inner surface of the cone 296 is a second conducting cone 298. This second cone is preferably provided with a number of randomly located venting holes 295 so as not to acoustically load the speaker 294. For the sake of clarity the spacing of these cones is exaggerated in Fig. 14. The inner cone 298 is connected to a high voltage source, indicated as a +300 v. terminal of the power supply, by a

high value resistor R299. The inner cone is also connected to an input terminal of a power amplifier 300 having a volume control 302 associated therewith, the latter being operated by a swell shoe 304. The output of the amplifier 300 is coupled to a number of speakers 306.

As the speaker cone 296 vibrates, its surface will break up into a very complicated vibration pattern in which the motions appearing at different areas on the cone are not in phase with each other. The resulting pulsating D. C. voltage on the internal cone 298 therefore corresponds to a superposition of a great number of waves. The simple geometric shape of wave as initially generated is thus completely destroyed and all co-relations between the instants of maxima and minima for the various harmonics are removed. This modified wave of intricate shape may subsequently be electrically superimposed with an octavely related wave having simple geometric contours and supplied to the speakers 306 without causing objectionable formants or tone quality beats.

A further modified form of the output system usable with the generating system of Figs. 12 and 12a is shown in Fig. 15. This system is similar to that shown in Fig. 14 except that a separate microphone and speaker are shown in the box 297. The speaker 310 is coupled to the output of amplifier 290 and a microphone 312 is spaced from the speaker 310. The microphone 312 is connected to the input of an amplifier 314 having a volume control 316 associated therewith, the latter being operated by a swell shoe 318. The output of the amplifier 314 is supplied to a plurality of speakers 306.

In view of the fact that the microphone will receive and superimpose a great many waves from various parts of the speaker cone, the simple geometric shape of wave as initially generated will be completely destroyed and all co-relations between the instants of maxima and minima for the various harmonics will be removed. This modified wave of intricate shape may subsequently be electrically superimposed with an octavely related wave having simple geometric contours and supplied to speakers 306 without causing objectionable formants or tone quality beats.

In Fig. 16 there is illustrated a substitute form of generating system in which the oscillators are substantially identical with the oscillator C1 shown in Fig. 12, except that the oscillators are operating continuously while the instrument is being played and the flute and string tone signals are keyed to bus bars which are connected to the terminals S1, F1, S2, and F2 of one of the output systems. As shown for the C1 oscillator in Fig. 16, the signal across a resistor R320, which is connected between ground and the terminal S, is impressed through a decoupling resistor R324, upon conductor 322 leading to the S1 terminal, whenever the C1 key 156 is operated to close its switch 324. Similarly when this key is operated, it closes a switch 326 to connect the F terminal, through a decoupling resistor R330, to a bus 328 leading to the F1 terminal. It will be noted that the switches operated by the C#1 key operate in the same manner as those of the C1 key, but that the D1 key has a switch 332 which connects the S terminal of oscillator D1 to a bus bar 336 and has a switch 333 which connects its F terminal to bus bar 337, the 336 bus bar being connected to the S2 terminal and the 337 bus bar being connected to the F2 terminal. If we should designate the keys, the switches of which make connections with the bus bars 322 and 328 as having mode "a" connections, and the keys whose switches make connection with bus bars 336 and 337 as having mode "b" connections, then the switching connections would, for successive semitone notes of the scale, be in the order a, a, b, b, a, a, b, b, a, a, b, b, a, a, b, b, a, a, b, b, a, a, b, b, a, a.

By making the key switch connections for successive pairs of octaves in this manner, $1\frac{1}{2}$ of the perfect fifth

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intervals as well as all of the octave intervals will have different types of connections, whereby when perfect fifth intervals are played, as for example C1 and G1, the outputs of the corresponding oscillators will be transmitted to different output terminals and will thereby be differently operated upon in the output circuits whether the output circuit be as shown in Fig. 12b, Fig. 13, Fig. 14, or Fig. 15. Using the same example, if the keys C1 and G1 were simultaneously depressed the third, sixth, ninth, twelfth, etc harmonics of the C1 note would have the same nominal frequencies as the second, fourth, sixth, eighth, etc. harmonics respectively of the G1 note. By having the unison and fifth waves which make up the perfect fifth interval divided into separate channels, the undesirable effects of superposition are relieved for this interval as well as for the octave interval. However, the superposition problem is not, in general, as serious for perfect fifth intervals as it is for octave intervals because the number of common frequencies between the unison and fifth waves is considerably less than in the case of the octave interval. Consequently, the undesired formant and tone quality beat effects are less objectionable. It will be noted that there is one perfect fifth interval for which the signals are not separated. This interval is preferably the F# to C# interval which is infrequent in most music. In addition, of course, this switching arrangement shown in Fig. 16 has all of the advantages of the tone switching arrangement shown in Fig. 12 since the signals from the unison and octave oscillators also are transmitted through different channels to the speakers.

It will also be noted that the V terminals of the oscillators whose keyed switches are connected in the "a" mode are connected by their resistors R168 to a conductor 340 to the V1 terminal of the vibrato apparatus, whereas those oscillators having switching connections of the "b" mode are connected through their resistors R168 and conductor 342 to the V2 terminal of the vibrato apparatus so that not only will most of the fifth and all of the octavely related notes be transmitted through different output channels but they will also have oppositely phased vibratos whenever the vibrato is turned on. This will further decrease greatly the possibility of having any tone quality beats in the sound produced, and will enhance the highly desirable chorus effect.

The foregoing arrangement of the switches and of the vibratos will be effective on all octavely related notes and on $\frac{1}{12}$ of the notes related as unison and fifth, and this will also be true of the vibrato effect when used to reduce the possibility of tone quality beats.

The various partials of a tone signal may also be displaced to different extents by the use of a reverberation apparatus such as shown in the patents to Laurens Hammond Nos. 2,211,205 and 2,230,836. An output system of this type is diagrammatically illustrated in Fig. 17. Conductor 225 corresponding to the similarly numbered conductor on Fig. 12b is connected to one of the input terminals of a reverberation apparatus 350 and the conductor 226 is connected to one of the input terminals of a signal reverberation apparatus 351, the other input terminals of the reverberation devices 350 and 351 being connected to ground. The outputs of these reverberation devices are connected to an amplifier 352 through decoupling resistors R354 and R355, and the output of the amplifier is supplied to a speaker 356.

By supplying the unison and octave signals to different reverberation devices the various partials are displaced in phase relative to one another in a more or less random manner so that the amplitude of the partials of the unison and its octave will combine statistically at the input of the amplifier 352. Assuming each partial of both the unison and the octave to have an amplitude of unity, the amplitude of the frequencies common to the unison and octave at the input of the amplifier 352 will have an average amplitude of 1.41, if the losses in the reverberation devices and in the decoupling resistors R354 and R355 be disregarded.

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It is not essential that alternate octave groups of tone signals be transmitted through one of the channels while the intermediate octave groups of tone signals are transmitted through a different channel. Stated negatively, unison and octave signals should never be transmitted through the same channel. For example, the signals for the notes C1, C3, and C5 might be transmitted through channel "a" and those for notes C2, C4, and C6 through channel "b." Then signals for the notes D1, D3, and D5 could be transmitted through channel "b" while signals for notes D2, D4, and D6 could be transmitted through channel "a," etc. Each of the various forms of output systems may be used with either of the tone signal generating systems or any other sources of electrical musical tone signals which are harmonically complex but which have relatively few alternations per cycle.

In the foregoing description the oscillators could, in each instance, be replaced by other sources of electrical tone signal generators which produce simple wave shape but harmonically complex tone signals. For example, they could be of the photo-electric, magnetic, capacitive, or pre-recorded type, and the moving part may rotate, vibrate, or move as a tape or wire in a magnetic recorder. Likewise, the signal transmission may be produced by capacitive, resistive, or inductive keying. Furthermore, it is not essential that there be a generator for each note of the scale. One oscillator may serve as the source of tone signals for several notes in the scale as shown in my prior application Serial No. 254,574 filed November 2, 1951, now Patent 2,681,585 issued June 22, 1954.

The basic principle which is herein claimed to be novel is the separation of octavely related tone signals from a set of electrical tone generators into a plurality of channels of far fewer number than there are playing keys or generators, and providing a wave form distorting apparatus in at least one of these channels to render the initially generated wave shape to be of a more intricate character. The wave form distorting apparatus may take the form of an acoustic vibrator (loud speaker or other electro-acoustic translating means), an electrical network having a variable time delay characteristic in the audio frequency spectrum, reverberation apparatus having wave form distorting properties, or may consist of any other kind of wave form distorting apparatus.

The essence of the invention is that unison and octave tone signals of given pitches are always transmitted through different output channels, at least one of which includes means greatly to distort the wave shape. The distortion may be accomplished by electrical, mechanical, or acoustical means.

I claim:

1. In an electrical musical instrument having at least three octaves of keys, the combination of a single set of generators capable of supplying complex wave electric tone signals of the chromatic scale throughout at least a three octave range, at least two separate amplifiers each having a speaker coupled to its output, and means operable by the keys for causing the outputs of one octave of generators to be supplied to the input of one amplifier and for causing the outputs of the generators of the adjacent octaves to be supplied to a different amplifier.

2. In an electrical musical instrument having a keyboard comprising a plurality of keys extending throughout a gamut of several octaves and including a first key, a second key spaced by an interval of an octave from the first key, and a third key intermediate the first and second keys; a single set of electrical complex wave tone signal sources associated respectively with the keys of the keyboard; first and second output systems; means operable by the first and third keys to cause their associated signal sources to supply signals to the first output system; and means operable by the second key to cause its associated signal source to supply a signal to the second output system.

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3. The combination set forth in claim 2, in which each of the output systems includes an individual loud speaker.

4. The combination set forth in claim 2, in which the signal sources comprise normally non-operating electrical tone signal generating devices, in which the means operable by the keys to cause their associated signal sources to supply signals to the output systems comprises an electrical power supply which when connected to a tone signal generating device will cause it to supply signals to the output system, and in which switches operable by the keys are provided to connect the power supply to the tone signal generating devices respectively.

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