ATTACK AND DECAY SYSTEM FOR A DIGITAL ELECTRONIC ORGAN
22 Claims, 12 Drawing Figs.

ABSTRACT: In an electronic organ, the actuation of keys in accordance with corresponding audible tones to be reproduced effects the gating of pulses into time slots of a time division multiplexed signal, the time slots of the multiplexed signal being structured in accordance with a desired assignment sequence to correspond to the keys and to be representative thereof for identifying each note capable of being generated by the organ. A set of note, or tone, generators with availability assignment control means for capturing a pulse in the multiplexed signal are each rendered responsive to a given captured pulse for generating the tone represented by that pulse. The appropriate tone is generated digitally in the form of amplitude samples of a waveform stored in a memory, and the amplitude samples are subsequently subjected to digital-to-analog conversion for ultimate production of the audible output of the organ. Attack and decay of the tone, or note, waveform envelope are simulated by appropriately scaling the amplitude samples at the leading and trailing portions of the waveform envelope.
FROM 32 AND GATES 8 OF DECODER 7
FROM 12 STAGES OF NOTE SECTION 2 (KEYBOARD COUNTER 1)

FIG. 3

MULTIPLEXED SIGNAL

SWITCHING ARRAY II

ENCODER 15

20-12
20-11
20-10
23

20-3
18

20-2

20-1

FIG. 3A

NOTE COUNTER

MASTER CLOCK

12

LOAD

SHIFT

SR 1
SR 2
SR 3
SR 11
SR 12

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FIG. 4

FIG. 5

MULTIPLEXED WAVEFORM (PULSES CORRESPONDING TO NOTES PLAYED)

RESET COUNTER ZERO

FIG. 6

MULTIPLEXED SIGNAL

GENERATOR ASSIGNMENT LOGIC

TONE GENERATORS (1-12)

FIG. 9

(SAMPLE POINTS)

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FIG. 7A

FIG. 7B

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ATTACK AND DECAY SYSTEM FOR A DIGITAL ELECTRONIC ORGAN

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention resides broadly in the field of electronic musical instruments, and is particularly adaptable for use in the electronic organ as a digital selection system for calling forth desired tones from those available to be produced by the organ, and for impressing upon the tone envelopes the appropriate attack and decay characteristics. The term "organ" is used throughout the specification and claims in a generic sense (as well as in a specific sense) to include any electronic musical instrument, and is scanned by a keyboard such as an electronic organ, an electric piano or accordion, and so forth, and in fact, the principles of the present invention are applicable to any musical instrument in which musical sounds are generated in response to the actuation of key switches, regardless of whether the switches are actuated directly, i.e., by the musician's fingers, or indirectly, e.g., by the plucking of strings.

The term "key" is also used in a generic sense, to include depressible keys, on-off switches, touch- or proximity-responsive (e.g., capacitance- or inductance-operated) devices, closable apertures (e.g., a hole in a "keyboard" of holes which when covered by the musician's finger closes or opens a fluidic circuit to produce a tonal response), and so forth.

2. Description of the Prior Art

The function of an electronic organ is to faithfully reproduce, or to simulate by electronic means, the sounds or tones developed by a true pipe organ upon selection of notes and other special effects by the organist. In order to provide other than an abrupt start and an abrupt end of the tone envelope generated when a particular key is depressed and released, respectively, it is desirable to simulate attack and decay of the tone by gradually increasing the tone envelope at the leading edge and gradually decreasing the envelope at the trailing edge. In conventional electronic organs, desired attack and decay may be conveniently handled by use of circuits having the necessary time constants or whose time constants may be adjusted according to the desired rise and fall of the waveform at the leading and trailing edges. Resistance-capacitance networks are commonly employed for such purpose.

In the copending application of G. A. Watson entitled "Multiplexing System For Selection Of Notes And Voices In An Electronic Musical Instrument," filed on even date herewith, and assigned to the same assignee as the present invention, there is described an electronic organ in which every key is associated with a tone generator and includes a memory containing different time waveforms associated with the respective keys and whereby to read in the appropriate sounding generated in response to the playing of the keys.

The tone generators which respond to the incoming multiplexed signal to bring forth the appropriate tones corresponding to those keys that have been actuated and deactivated. This parallel format is continuously converted to a serial format to provide information regarding key actuation in the form of pulses at appropriate time of the time division multiplexed signal which is supplied to the tone generating section of the organ. Each time slot of the multiplexed signal is representative of a key that can be set or set of a key that can be associated with the respective keys and thereby to result in the appropriate sounds being generated in response to the playing of the keys.

Such an arrangement permits reduction of complexity that is usually found in electronic organs and in particular permits elimination of a substantial number of wires and cables that are usually required between the keyboards and the tone generators. Furthermore, since the digital electronic organ of the aforementioned Watson application provides assignment in a simple and efficient manner of a small number of tone generators, relative to the number of keys available, to the keys which have actuated, there is a further reduction in complexity of mapping the subset of depressed keys into the available tone generators by means of special wiring arrangements, as in conventional arrangements. Still further, the digital electronic organ overcomes such difficulties as may occur when a key switch has faulty or dirty contacts, a situation that would ordinarily lead to intermittent electrical contact and discontinuity of tone. By use of a multiplexed signal, the presence of a pulse in a particular time slot of a repeating signal is sufficient to represent the actuation of the corresponding key, and less than perfect contact is required to produce that pulse.

Each of the limited number of tone generators provided in the digital electronic organ of the aforementioned Watson application is associated with generator assignment logic constructed and arranged to assign an available tone generator to an incoming pulse in the multiplexed signal which has not yet captured a tone generator. Each tone generator includes a memory means storing digital representations of amplitudes of the waveform to be synthesized at a large number of sample points. When the tone generator is captured by a pulse, the memory means associated with that tone generator is accessed to read out amplitude samples in accordance with the frequency of the tone to be generated.

It is a principal object of the present invention to provide an attack and decay simulation system by which the amplitude of the leading and trailing portions of the note envelope of a digital electronic organ are appropriately scaled.

SUMMARY OF THE INVENTION

Briefly, according to the present invention, the duration of the attack or decay is controlled by a counter which may be selectively enabled to count timed pulses having a rate independent of the note frequency, or to count cycles or half cycles of the specific note frequency. In essence, the counter serves to determine the abscissa in a graph of amplitude versus time for the attack or decay. The ordinate or amplitude scale of the graph is provided by a plurality of amplitude scale factors stored in a fixed memory accessed by the counter. The scale factors are read from the fixed memory required and supplied to a multiplier which receives as a second input the digital amplitude samples being read from the tone generator memory, the multiplier forming the product of these two inputs to scale the leading and trailing portions of the note waveform.

In a preferred embodiment of the invention, the count is initiated when the note generator is assigned a pulse and the attack mode is entered. Unless the attack system is disabled, a positive attack is provided in which the counter is forced to complete the attack regardless of whether or not the key remains depressed. When the key is subsequently released, and the corresponding pulse fails to appear in the multiplexed signal, the count for decay is initiated. If the pulse representative of the same key should reappear during decay, indicating that the latter key has again been actuated, the attack mode is reassembled. However, if the key is again released prior to completion of attack, the system is constructed and arranged such that positive attack is not in effect and the decay mode is reinitiated immediately. This operation simulates that which occurs in a pipe organ.

BRIEF DESCRIPTION OF THE DRAWINGS

In describing the present invention, reference will be made to the accompanying FIGURES of the drawings in which:

FIG. 1 is a simplified block diagram of a system for producing a time division multiplexed signal containing a recycling sequence of time slots each associated with a particular key of
the organ and in which each time slot containing a pulse is indicative of the actuation of the associated key;

FIG. 2 is a circuit diagram of an exemplary decoder for use in the system of FIG. 1;

FIG. 3 is a more detailed circuit diagram of the switching array and encoder used in the system of FIG. 1;

FIG. 4 is a circuit diagram of an alternative encoder to that shown in FIG. 3, for use in the system of FIG. 1;

FIG. 5 is illustrative of a multiplex waveform developed by the system of FIG. 1 in response to actuation of selected keys;

FIG. 6 is a simplified block diagram of generator assignment and tone generating apparatus for processing the multiplexed signal produced by the system of FIG. 1 to develop the desired tones as an audible output of the organ;

FIGS. 7A and 7B together constitute a circuit diagram of one embodiment of the tone generator assignment logic for the system of FIG. 6;

FIG. 8 is a block diagram of a tone generator suitable for synthesizing the frequency of every note capable of being played in the organ, for use with the assignment logic of FIGS. 7A and 7B in the system of FIG. 6;

FIG. 9 is illustrative of a complex waveshape of the type produced by a pipe organ, and of the sample points at which amplitude values are taken, for simulation at selected note frequencies; and

FIG. 10 is a block diagram of a preferred embodiment of an attack and decay control unit for use in an electronic digital musical instrument of the type shown and described with reference to the preceding FIGURES of drawing.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring to FIG. 1, the keyboard multiplexing system or note selection system includes a keyboard counter 1 which is implemented to provide a specified count for each key of each keyboard (including manuals and pedal divisions) of the organ. If, for example, the electronic organ in which the multiplexing system is used has four keyboards, such as three manuals and a pedal board, each encompassing up to eight octaves, then keyboard counter 1 should have the capability of generating 4×8×12=384 separate counts (digital words). It is essential that the counter be capable of developing a count representative of every key on every keyboard of the organ; however, it may be desirable to provide a counter that can produce a count greater than the number of available keys in order to have available certain redundant counts not associated with any keys. Such redundancy is readily provided by simply utilizing a counter of greater capacity than the minimum required count.

Keyboard counter 1 is divided into three separate sections (or separate counters) designated 2, 3 and 4. The first section (designated 2) is constructed to count modulo 12 so as to designate each of the 12 keys associated with the 12 notes in any octave. The second section (designated 3) is adapted to count modulo 8, to specify each of the eight octaves encompassed by any of the four keyboards. The last section (designated 4) is designed to count modulo 4 to specify each keyboard of the organ. Therefore, the overall keyboard counter is arranged to count modulo 384, in that at the conclusion of every 384 counts, the entire set of keyboards have been covered (scanned) and the count repeats itself. To that end, each counter section may be composed of a separate conventional ring counter, the three counters being connected in the typical cascaded configuration such that when section 2 reaches its maximum count it advances the count of counter-section 3 by one, and will automatically initiate a repetition of its own count. Similarly, attainment of its maximum count by counter-section 3 is accompanied by advancement of the count of section 4 by one.

Advancement of the count of counter 2 is accomplished by application of clock pulses thereto from a master clock source

5 which delivers clock pulses at a sufficiently rapid repetition rate (frequency) to ensure resolution of depression (actuation) and release (deactuation) of any key on any keyboard, i.e., to supply a pulse at the instant of either of these events. Scanning of all keyboards of the organ at a rate of 200 or more times a second is deemed quite adequate to obtain this desirable resolution. For the exemplary counter set forth above, this is equivalent to a minimum of 200×384=76,800 counts per second, so that a master clock delivering clock pulses at a rate of 100 kc./s. is quite suitable.

A total of four lines emanate from counter 4, one line connected to each ring counterstage, to permit sensing of the specific keyboard which is presently being scanned. Similarly, the eight lines are connected to the eight ring counterstages, respectively, of octave counter 3 to detect the octave presently being scanned. Thus, a total of 12 lines extend from counters 3 and 4, and these 12 lines can carry signals indicative of 32 (8×4) possible states of the keyboard counter. The specific one of the 32 states, representative of a particular octave on a particular keyboard, which is presently being scanned is determined by use of a decoder circuit 7 connected to the output of counter 3, and being numbered 32 AND gates designated 8–1, 8–2, 8–3, 8–32 (FIG. 2), each with two input terminals and an output terminal. The gates are arranged in four groups of eight each, with every gate of a particular group having one of its two input terminals (ports) connected to one of the four lines of counter 4. Distinct and different ones of the eight lines from counter 3 are connected to the other input terminal of a respective one of the eight AND gates of that group. A corresponding signal exists for each group of AND gates, with the only difference being that each group is associated with a different output line of counter section 4. Using this arrangement, the decoder logic designates every octave of keys in the organ by a respective drive pulse when a count corresponding to that octave is presently contained in the counter.

The output pulses deriving from the AND gate (or drivers) of decoder circuit 7 are supplied on respective ones of 32 bus bars (or simply, buses), generally designated by reference numeral 10, to a keyboard switching array 11. From the preceding description, then, it will be clear that array 11 has one input bus 10 for every octave of keys in the organ (including every octave on every keyboard), and that a drive pulse will appear on each input bus approximately 200 times per second, in a manner to ensure adequate operation of the keys. Switching array 11 also has 12 output buses, generally designated by reference number 12, each to be associated with a respective one of the 12 notes (and hence, the 12 keys) in any given octave.

Array 11 is basically a diode switching matrix, in which spaced input buses 10 and spaced output buses 12 are orthogonally arranged so that an intersection or crossing occurs between each input bus and each output bus (see FIG. 3), for a total of 384 intersections, one for each count of the keyboard counter 1. As is typical in this type of matrix, the crossed lines or buses are not directly interconnected. Instead, each line is connected to a "jump" diode, such as that designated 13 in FIG. 4, is connected between the input bus 10 and the output bus 12 at each intersection, the diode poled for forward conduction (anode-to-cathode) in the direction from an input bus 10 to an output bus 12. Wired in series circuit or series connection with each diode 13 is a respective switch 14 which is normally open, but is closed in response to a distinct respective one of the keys of the organ, such that depression of the associated key produces closure (close circuiting) of the switch 14 whereas release of the associated key results in return of the switch to its open state. Alternatively, each of switches 14 may itself constitute a respective key of the various keyboards of the organ.

While switch 14 is shown schematically as being of mechanical single-pole, single-throw (SPST) structure, it will be understood that any form of switch, electronic, electromechanical, electromagnetic, and so forth, may be utilized,
the exact nature of the switch depending primarily upon the nature of the energization produced upon operation of the associated key. Switch 14, then, is adapted to respond to the particular form of energization or actuation produced upon operation of a key on any keyboard (or, as observed above, may itself constitute the key), to complete the circuit connecting associated diode 13 between a respective input bus 10 and a respective output bus 12 at the intersection of those buses when the key is depressed, and to open the circuit connecting the diode between respective input and output buses at that intersection when the key is released. Positive pulses occurring at the rate of approximately 200 per second, for example, according to the timing established by master clock 5, are transferred from input bus 10 to output bus 12 via the respective diode 13 and closed switch 14 when the associated key is depressed. While a switch alone (i.e., without the series connected diode) would serve the basic purpose of transferring a signal between the input and output lines of array 11, the diode provides a greater degree of isolation from sources of possible interference (noise) and acts to prevent feedback from output back to input.

In FIG. 3, the output buses 12 from switching array 11 are connected to an encoder circuit 15 to which are also connected the 12 output lines, generally designated by reference number 16, from keyboard counter section 2. To produce an orderly arrangement in which each key of the organ is assigned a distinct and different time slot in a time-division multiplex waveform, the switches 14 associated with the respective keys are connected in sequence in the switching array 11. Assume, for example, that specific output bus 17 of the switching array is to be associated with note A of any octave, a second output bus 18 is to be associated with note B of any octave, and so forth. Then switches 14 in the row corresponding to output bus 17 in array or matrix 11 are associated with the keys corresponding to the note A in each octave of keys in the organ. The column position of each switch 14 in matrix 11 corresponds to a specific octave of keys in the organ, and hence, to a specific octave encompassed by a specific keyboard of the organ.

Each of the output buses 12, including 17, 18, and so forth, is connected to one of the two input ports or terminals of a respective AND gate of the twelve AND gates 20-1, 20-2, 20-3, 20-12, of encoder circuit 15. An output lead 16 of each counter section 2 associated with a key is designated the count for a particular note (key) in a given octave is connected to the remaining port of an encoder circuit AND gate having as its other input a pulse on the output bus 12 associated with that same note. A similar arrangement is provided for each of the remaining 11 output lines 16 of counter section 2 with respect to the AND gates 20 and the output buses 12. Thus, for example, if output bus 17 (associated with the row of switches 14 in matrix 11 for note A) is connected to one input terminal of AND gate 20-1, then output line 22 from the stage of counter 2 designating the count associated with note A is connected to the remaining input terminal of gate 20-1. The output terminal of each of AND gates 20 is connected to a respective input terminal of OR gate 23, the output of which, constituting the output signal of the encoder circuit. By virtue of its structure, encoder circuit 15 is effective to convert the parallel output of array 11 to a serial output signal in accordance with the scanning of output buses 12 as provided by the advancing and repeating count sensed in the form of pulses (at a rate of about 200 per second) appearing on output lines 16. The end result of this circuitry is the production of a time-division multiplex (TDM) signal on a single conductor 25 emanating from encoder 15.

As an alternative to the specific logic construction shown for encoder 15 in FIG. 3, the encoder may have the circuit configuration exemplified by FIG. 3A. Referring to the latter FIGURE, the encoder includes a shift register 80 having 12 cascaded stages designated SR1, SR2, SR3, . . . , SR12, each connected to a respective output bus 12 of switching matrix 11 to receive a respective output pulse appearing thereon. The shift register stages are loaded in parallel with the data read from switching array 11 on output buses 12, in response to each of the pulses appearing (i.e., each time a pulse appears) on one of the 12 output leads 16 of note counter 2. That one output of the note counter which is to supply the load command for all 12 stages of shift register 80 is selected to permit the maximum amount of settling time to elapse between each advance of octaves. In this example, the first stage counter and keyboard counter 4 and the loading of the shift register. In other words, it is extremely desirable that the data to be entered into the shift register from the switching array be stabilized to the greatest possible extent, and this is achieved by allowing the counters whose scanning develops this data, to settle at least immediately prior to loading. Thus, the first note counterstage, or one of the early stages, is selected to provide "load" pulses to shift register 80.

"Shift" pulses are supplied to the shift register by master clock 5, which also supplies note counter 2, to shift the contents of each shift register stage to the next succeeding stage except during those bit times when the shift pulse is preempted by a load pulse from the note counter. Accordingly, shift register 80 is parallel loaded, and the date contents of the register are then shifted. The register format on encoder output line 25 until a 1-bit pause occurs when another set of data is parallel loaded into the shift register, followed again by serial readout on line 25. This serial pulse train constitutes the time division multiplexed output signal of encoder 15 just as in the embodiment of FIG. 3, except that with the FIG. 3A configuration, decoder 7 (and the counters 3 and 4 supplying pulses thereto) undergo a greater amount of settling time.

It will be observed that this operation constitutes a parallel-to-serial conversion of the information on output buses 12 to a time-division multiplexed waveform on the output line 25 of encoder 15.

In the TDM signal, each key has a designated time slot in the 384 time slots constituting one complete scan of the keyboard of the organ. In the specific example of the time base provided by master clock 5, the TDM waveform (shown by way of example in FIG. 5) is initiated about 200 times per second. This waveform contains all of the note selection information, in serial digital form on a single output line, that had heretofore required complex wiring arrangements. This waveform developing counter sections 2 and encoder 15 in an example of the operation of the circuitry thus far discussed. It should be observed first, however, that all of the counter and logic circuitry described up to this point can be accommodated within a very small volume of space by fabrication in integrated circuit form using conventional microelectronic manufacturing techniques.

When the main power switch for the electronic organ is turned on, all components are energized to an operational state, the master clock delivering pulses to keyboard counter 1 at the aforementioned rate. Upon depression of a key on any keyboard of the organ, including the manuals and pedal divisions, a respective switch 14 associated in series connection with a diode 13 at the intersection between the appropriate input bus 10 and output bus 12 of the switching array 11 is closed, thereby connecting the two buses to supply pulses appearing on a given bus 10 from decoder 7, to the appropriately connected output bus 12 for application to encoder 15. If, for example, the key that was depressed is associated with note C in the second octave, C4 appears in the appropriate time slot of the multiplexed signal emanating from encoder 15 and will repetitively appear in that time slot in each scan of the keyboards of the organ as long as the key remains depressed. To say, a pulse appears on output line 10 of decoder 7 associated with the second octave in the manual being played, in accordance with the scan provided by master clock 5, as the counterstage associated with that octave is energized in keyboard counter octave section 3 and the counterstage associated with that manual is energized in section 4 of the keyboard counter. The connection between the appropriate
input bus 10 and output bus 12 of switching array 11 for the particular octave and keyboard under consideration is affected by the depression and continued operation of the key associated with the switch 14 for that intersection in the array. Since, as previously stated, each switch is associated with a particular note (key) and is positioned in a specific row of the switching array, a signal level is thereby supplied to the appropriate output bus 12 of the switching array arranged to be associated with that note. Each time the specified note, here the note C5, is scanned in the sequence of count in the note section 2 of the keyboard counter, a second input is provided to the AND gate 20 receiving the signal level on output bus 12, and a pulse is produced. Thus, in case of any operation, the pulse which appears at the output of OR gate 23 always appears in the identical specified time slot in the multiplexed signal for a specific note associated with a particular key on a particular keyboard of the organ.

If more than one key is depressed, regardless of whether one or more keyboards is involved, operation corresponding to that described above for a single depressed key is affected for every operated key. Thus, for example, assume that the key associated with note C5 is played on one manual, the note B5 is played on a second manual, and the notes D6, E6, and G6 are played on a third manual, the associated keys being depressed substantially simultaneously to produce desired simultaneous reproduction of all notes as the audio output of the organ. Under these conditions, the associated switches 14 in the switching array 11 are closed to provide through connections between the respective input buses 10 and output buses 12 for the specific octaves and manuals involved. As the appropriate AND gates 20 in encoder 15 are supplied with gating signals from the sequentially energized counterstages of note section 2, during the scanning operation provided by that keyboard counter section, pulse levels appearing on output buses 12 for which switches 14 have been closed are gated in the appropriate time slots of the multiplexed signal on the output lead 25 from OR gate 23 of encoder 15, for the specific notes involved.

An example of the multiplex signal waveform thus generated is shown in FIG. 5. While the pulses appearing in the time slots associated with the specific notes mentioned above are in a serial format or sequential order, their appearance is repetitive during the interval in which the respective keys are actuated. Hence, the effect is to produce a simultaneous reproduction of the notes as an audio output of the organ, as will be explained in more detail in connection with the description of the tone generation section.

Referring now to FIG. 6, the multiplexed signal arriving from encoder 15 is supplied to generator assignment logic network 26 which functions to assign a tone generator 28 to a depressed key (and hence, to generate a particular note) when the associated pulse first appears in its respective time slot in the multiplexed signal supplied to the assignment logic. If only 12 tone generators 28 are available in the particular organ under consideration, for example, the assignments are to be effected in sequence (order of availability), and once particular pulses have been directed to all of the available generators (i.e., all available tone generators have been "captured" by respective note assignments), the organ is in a state of saturation. Thereafter, no further assignments can be made until one or more of the tone generators is released. The availability of 12 (or more) tone generators, however, renders it extremely unlikely that the organ would ever reach a state of saturation since it is quite improbable that more than 12 keys would be depressed in any given instant of time during performance of a musical selection. The output waveforms from the captured tone generators at the proper frequencies for the notes being played, are supplied as outputs to appropriate wave shaping and amplification networks and thence to the acoustical output speakers of the organ. If the tone generators 28 supply a digital representation of the desired waveform, as in the case in one embodiment to be described, then the digital format is supplied to an appropriate digital-to-analog converter, which in turn supplies an output to the wave shaping network.

At any given instant of time, each tone generator 28 may be in only one of three possible states, although the concurrent states of the tone generators may differ from one tone generator to the next. These three states are as follows:

1. A particular note represented by a specific pulse in the multiplexed signal has captured (i.e., claimed) the tone generator;
2. The tone generator is presently uncaptured (i.e., unclaimed or available), but will be captured by the next incoming pulse in the multiplexed signal associated with a note which is not presently a tone generator captor; and
3. The tone generator is present but not available, and will not be captured by the next incoming pulse.

It should be apparent from this delineation of possible states that any number of the tone generators provided (12, in this particular example) may be in one or the other of the states designated (1) and (3), above, but that only one of the tone generators can be in state (2) during a given instant of time. That is, one and only one generator is the next generator to be claimed. When the specific tone generator in state (2) is claimed by an incoming pulse, the next incoming pulse which is not presently claiming a tone generator is to be assigned to the generator that has now assumed state (2). For example, if the third tone generator (03) of the 12 generators is captured by an incoming pulse (note representation) and the fourth generator is captured by the next pulse, assume that the note selection, then tone generator 04 is unavailable to the next incoming pulse, and the privilege of capture must pass to the next tone generator which is not presently in a state of capture. If all of the tone generators are captured, that is, all are in state (1) as described above, then the organ is saturated and no further notes can be played until at least one of the tone generators is released. As previously observed, however, the saturation of an organ having 12 (or more) tone generators is highly unlikely.

Generator assignment system 26 is utilized to implement the logic leading to the desired assignment of the tone generators 28, and thus to the three states of operation described above. An exemplary embodiment of the generator assignment logic is shown in FIGS. 7A and 7B. Referring to FIG. 7A, a ring counter 30, or a 12-bit recirculating shift register in which one and only one bit position is a logical "1" at any one time, is used to introduce a claim selection, i.e., to initiate the capture, of the next available tone generator in the set of tone generators 28 provided in the organ. A shift signal appearing on line 32 advances the "1" bit position from the counterstage to the next, i.e., shifts the "1" to the next bit position. Each bit position is associated with and corresponds to a particular tone generator, so that the presence of the logical "1" in a particular bit position indicates selection of the tone generator to be claimed next, provided that it is not already claimed.

Each time the logical "1" appears in a stage of shift register 30, a "claim select" signal appears on the respective output line 34 associated with the stage. This "claim select" signal is supplied in parallel to one input of a respective one of AND gates 35, on line 36, and to further logic circuitry (to be described presently with reference to FIG. 7B), on line 37. The output line of each of AND gates 35 is connected to a separate and distinct input line of an OR gate 40 which, in turn, supplies an input to an AND gate 42 whose other input constitutes pulses from the master clock 5.

In operation of the portion of the generator assignment logic shown in FIG. 7A, assume that shift register stage 02 contains the logical "1." That stage therefore supplies "claim select" signal to the respective associated AND gate 35 and, as well, to further logic circuitry on line 37. If this further logic circuitry determines that the associated note generator may be claimed, a "claimed" signal is applied as the second input to the respectively associated AND gate 35. Since both inputs of that AND gate are now "true," an output pulse is furnished via OR gate 40 to the synchronization gate 42. The latter gate produces the "shift" pulse on line 32 upon simultaneous occurrence of the output pulse from OR gate 40 and a clock pulse from master clock 5. Accordingly, the logical "1"
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is advanced one bit position, from stage 02 to stage 03 of shift register 30, in preparation for the claiming of the next tone generator.

Suppose, however, that the tone generator 28 corresponding to stage 03 is already claimed by a previous note pulse in the multiplexed signal. In that event a “claimed” signal appears as one input to the associated AND gate 35, and with the “claim select” signal appearing as the other input to that gate by virtue of stage 03 containing the single logical “1,” another shift pulse is immediately generated on line 32 to advance the logical “1” to stage 04 of the shift register. Similar advancement of bit position of the “1” continues until an unclaimed tone generator is selected. If it should happen that no note is presently being selected on a keyboard of the organ at the time when an unclaimed tone generator is selected, the “1” remains in the shift register stage associated with the selected tone generator until such time as a “claimed” signal is concurrently applied to the respective AND gate 35, i.e., until the selected tone generator is claimed, because until that time no further shift signals can occur.

Referring now to FIG. 7B, each tone generator also has associated therewith a respective part of the generator assignment logic as shown in FIG. 7A. In other words, the circuitry of FIG. 7B, with minor exceptions to be noted in the ensuing description, is associated with the i-th tone generator (where i = 1, 2, 3, . . ., 12), and since each of these portions of the assignment logic is identical, a single showing and description will suffice for all. An AND gate 58 has three inputs, one of which represents a “pointed” signal derived from the counter clock (this being supplied in parallel to the AND gates 50 of the remaining identical portions of the assignment logic for the other tone generators, as well), a second of which is the “claim select” signal appearing on line 37 associated with the i-th stage of shift register 30 (FIG. 7A), and the third of which is a signal, on line 52, indicating that the pulse in the multiplexed signal has not captured any tone generator as yet. Of course, these signals are not present unless the respective events which produce them are actually occurring but if all three signals are simultaneously presented as inputs to AND gate 50, a “set” signal is applied to a claim flip-flop 53 to switch that flip-flop to the “claimed” state and simultaneously therewith to supply a “claimed” signal to the AND gate 35 associated with the i-th stage of shift register 30 and to the respective associated tone generator.

A modulo 364 counter 55 is employed to permit recognition by the respective portion of the generator assignment logic of the continued existence in the multiplexed signal of the pulse (time slot) which resulted in the capture of the associated tone generator. To that end, counter 55 is synchronized with keyboard counter 1 (also a modulo 364 counter) by simultaneous application of a master clock 5. The count of each counter 55 associated with an uncaptured tone generator is maintained in synchronism with the count of keyboard counter 1 by application of a reset signal to an AND gate 58 each time the keyboard counter assumes a zero count; i.e., each time the count of the keyboard counter repeats. However, that reset signal is effective to reset counter 55 only if the associated tone generator is uncaptured. The latter information is provided by the state of flip-flop 53, i.e., a “not claimed” signal is supplied as a second input to AND gate 58 whenever flip-flop 53 is in the “unclaimed” state.

When the flip-flop (and hence, the associated tone generator) is claimed, however, it is desirable to indicate the time slot occupied by the pulse which effected the capture, and for that reason a “reset” signal is applied to counter 55 at a time a time slot output signal is derived from AND gate 50. Thus, in the captured state, the zero count of counter 55 occurs with each repetition of the “capturing” pulse in the TDM waveform. Such information is valuable for a variety of reasons; for example, to prevent capture of an already captured tone generator when the zero count continues to appear simultaneously with a pulse in the TDM waveform, and to provide a “key released” indication when the zero count is no longer accompanied by a pulse in the TDM waveform. Capture prevention is effected by feeding a signal representative of zero count from counter 55 to the appropriate input terminal of an OR gate 60 associated with all of the tone generators and their respective generator assignment logic. The logical “1” supplied to OR gate 60 is inverted so that simultaneous identical logical inputs cannot be presented to AND gate 50. On the other hand, when the zero count is merely synchronized with the zero count of the keyboard counter and is not the result of capture of the associated tone generator it does not interfere with subsequent capture of that tone generator since it does not occur simultaneously with a pulse in the TDM signal. A “key release” indication is obtained by supplying the “zero count” signal to an AND gate 62 to which is also supplied an output signal developed from counter 55 connected to receive inputs from the TDM signal. If the zero count coincides with a pulse in the multiplexed signal, the inversion of the latter pulse prevents an output from AND gate 62, and this is proper because the coincidence of the zero count and the TDM pulse is indicative of continuing depression of the key which has captured the tone generator. Lack of coincidence is indicative that the key has been pressed and asserted in the “key release” signal. Supplying of the keyboards is sufficiently rapid that any delay which might exist between actual key release and initiation of the “key release” signal is negligible, and in any event is undetectable by the human senses. Furthermore, the generation of a false “key release” signal when the tone generator is presently unclaimed, as a result of a zero count error occurring in counter 55 synchronized with the zero count of the keyboard counter and the simultaneous absence of a pulse in the TDM signal, can have no effect on the audio output of the organ since the associated tone generator is not captured and is therefore not generating any tone. In any case, the “key release” signal deriving from AND gate 62 is supplied to attach decay logic of the tone generator to initiate the decay of the generated tone. The “set claim” signal output of AND gate 56 that occurs with the simultaneous appearance of the three input signals to that gate is utilized to provide a “key depressed” indication to the attack/decay circuitry of the tone generator (and to percussive controls, if desired), as well as to provide its previously recited functions of “setting” flip-flop 53 and “resetting” counter 55.

The assignment logic embodiment of FIGS. 7A and 7B may be associated with only a small number of tone generators (12, in the example previously given), the exact number being selected in view of the cost limitations and the likely maximum number of keys that normally may be actuated simultaneously. In that case, each tone generator must supply every desired frequency corresponding to every note in every octave that may be played during its active time. Then all digital tone generators for the series or sequence, and all digital tone generators for the exemplary configuration shown in block diagrammatic form in FIG. 8 is employed.

Before describing the cooperative structural and functional relationships between the elements of the tone generator shown in FIG. 8, it is instructive to consider some of the available alternatives in the construction and operation of digital tone generators for the waveform at a series or sequence, of uniformly spaced sample points. The digital sample point values thus generated are subsequently converted to analog form. The sample points are preferably uniformly spaced because such a format permits the most direct analysis, and therefore the most direct synthesis, of the desired waveform. If desired, the uniform spacing of sample points may be such that there is provided an integral number of samples per cycle for each
note frequency to be generated. Such a technique requires a sampling rate that varies directly with the frequency. Alternatively, the samples may be spaced uniformly in time, in which case the phase angle between sample points varies with the frequency of the note to be generated. Although the synthesis of a multiplicity of note frequencies can be implemented for either technique, using a single clock frequency, the preferred frequency synthesis technique is that in which the phase angle between the sample points synthesis technique is that in which the phase angle between the sample points varies with frequency, i.e., in which the sampling rate is fixed for all note frequencies to be generated, and the various generated note frequencies are produced as a result of the different phase angles.

FIG. 8 shows, in block diagram form, a specific exemplary system to generate the required note frequencies of the organ from a memory containing amplitude samples of the desired waveform obtained at uniformly spaced points in time. The sample points are accessed at a fixed, single clock frequency for all note frequencies to be generated and the phase angle between the sample points thereby varies with the frequency of the note to be generated. The tone generation circuitry establishes a basic memory of phase angle calculator 100, a phase angle register 101, a sample point address register 102, a read-only memory 103, an address decoder 103a, an accumulator 104, a sampling clock 105, and a comparator 107. As will be apparent hereafter, the phase angle calculator 100 and the read-only memory 103 may be shared by all of the tone generators 28. In addition, each tone generator is addressed or accessed individually and in sequence and thus once in each cycle of addressing all tone generators. For that reason, the sampling clock 105 may comprise a clock rate provided by a master sampling clock, successive clock pulses of which are directed to the series of tone generators. The sampling clock addressed to a given tone generator is thus at a rate comprising the pulse repetition rate of the master sampling clock divided by the number of tone generators provided for the organ. The read-only memory may be addressed by all tone generators, the accumulator 104 may be a composite structure associated with appropriate gating circuitry related to each tone generator for accumulating the information read from the memory 103 in response to accessing thereof by a given tone generator.

When a claim flip-flop of the tone generator assignment logic, such as flip-flop 53 (FIG. 7B), is switched to the claimed state in accordance with capturing a pulse in the incoming multiplexed waveform by a given tone generator 28, the phase angle calculator 100 is instructed to determine the appropriate phase angle for the frequency of the note to be reproduced as identified by the captured pulse. A determination of the value of the phase angle constant, and hence, of the particular note corresponding to the key that has been actuated, is initiated by supplying both the count from the main keyboard counter 1 and the count of the modulo 384 counter 55 (e.g., of FIG. 7B) associated with the captured flip-flop, and which is reset to zero upon capture, to a count comparator 107. Comparator 107 subtracts the count of counter 55 from the count of the keyboard counter 1 and supplies a number representative of the difference, and hence, representative of the time slot position corresponding to a particular note (i.e., that note which captured the flip-flop), to phase angle calculator 100. The difference computed by comparator 107 will always be positive, or zero, because the computation is elicited from the comparator only when the associated flip-flop 53 is captured and at that moment counter 55 is reset to zero, whereas the keyboard counter 1 probably has some greater count or contains a least count, i.e., zero.

On the basis of the difference count supplied by comparator 107, calculator 100 is informed as to the note for which the phase angle calculation is to be performed, i.e., the note and thus the frequency to be produced by the tone generator. The calculator 100 may compute the phase angle as a function of the frequency of the note to be reproduced and of the number of memory sampling points of the waveform in storage and thus as approximately equal to the phase angle of the fundamental between adjacent memory sampling points for the frequency to be produced. An alternative embodiment of the phase angle calculator 100 is a conventional storage unit with look-up capabilities, or simply a memory from which the correct phase angle is extracted when the memory is suitably addressed with the identification of the count of the captured flip-flop. Alternatively, the contents of a memory with look-up capabilities and of a calculator capable of computation for determination of the phase angles may be employed. The synthesis of note frequencies in accordance with the digitally stored waveform sample points may be arbitrarily as accurate as desired and, in effect, provides a true equally tempered scale of the synthesized note frequencies wherein the notes at the scale differ by an increment of a memory with look-up capabilities.

The phase angle thus developed is supplied to and stored in the phase angle register 101. Thus, upon capture of a given tone generator, a command control means such as flip-flop 53 (FIG. 7B) of each state of the phase angle calculator 100, a clock control means that controls the operation of the comparator 107 and, in turn, the phase angle determination function of the phase angle calculator 100 for the given note frequency to be generated, for supply of that phase angle to the register 101. Since this operation must precede the addressing function, a delay may be provided (as by use of a delay multivibrator 106) to actuate a switch 108 for passage of pulses from the sample and hold source 105 (which may be an appropriately gated pulse from a master sampling clock source) to the registers 101 and 102.

If desired, the sample point address register 102 may be cleared when claim flip-flop 53 reverts to a noncaptured state, so that it is prepared for entry of information from the phase angle register 101 upon each calculation. However, it is important to note that during accessing of the memory it is not the absolute value thereof which is significant in the control of the rate of read out of the memory 103 and thus the cyclic frequency of read out of the memory and, ultimately, the frequency of the note reproduced by the given tone generator.

Once each sampling clock time as determined by the sampling clock source 105, the phase angle value maintained in the register 101 as long as that tone generator is captured by a given pulse.

Thus, once each clock time, the phase angle register value, comprising a digital binary word, is added to the sample point address register value and correspondingly, for each such clock time, the memory location corresponding to the sample point address then existing in the register 102 is accessed. As a practical matter, only a relatively small, finite set of amplitudes can be stored in the memory 103, because of practical limitations on its capacity, and thus only a finite number of addresses are available. Furthermore, the registers such as 101 and 102 must be of a finite, practical length. In particular, the length of the phase angle register 101 is determined by the accuracy with which the frequency of the note is to be generated. The frequency actually produced will be exactly the value of the phase angle in register 101 times the memory sampling rate. The sample point address register 102, on the other hand, must be sufficiently long to accept data from the phase angle register 101. The register 102, however, preferably includes additional bit positions which are not used, or not used at all times, for accessing the memory. In this respect, it will be apparent that one bit position in the register 102 is scaled at one cycle of the fundamental of the frequency
of the note to be generated. A set of next successive less significant bits may therefore specify the sample point address in accordance with the function of the decoder 103a. The more significant bits of the register 102 may be used to count numbers of cycles of the waveform for various control functions not pertinent. In addition, by selecting appropriate bit positions by means of decoder 103a, the frequency of the note reproduced may be readily adjusted to different octaves. That is, a 1-bit positional shift constitutes division or multiplication by two, depending upon direction of shift. For example, if the most significant bit is numbered 1 and thus bit positions 2 through 6 comprise the sample point address bits normally used for an 8 foot voice, then a 16 foot voice can be obtained by using bits 1 through 5. Correspondingly, a 4 foot voice can be obtained by using bits 3 through 7 as the sample point address bits.

The read-only memory 103 contains digital amplitude values of a single cycle of the complex periodic waveform to be reproduced for all note frequencies. That is to say, the same complex periodic waveform is to be reproduced for each note frequency, the only difference being the frequency at which the complex waveform is reproduced.

Referring to FIG. 9, illustrating a typical complex waveshape 110 of the type that may be produced by a pipe organ, the wave may be sampled at a multiplicity of points, shown as vertical lines in the Figure, to provide the amplitude data for storage in memory 103. If absolute amplitude data is stored in register 102, then the data is accessed according to the actual amplitude of the output waveform at the respective sample points (i.e., with respect to a "zero" level at time axis 111). In that event, the digital amplitude data successively read from the memory may be applied directly to an appropriate digital-to-analog conversion system. On the other hand, if incremental amplitude information (i.e., simply the difference in amplitude between the present sample and the immediately preceding sample) is stored in memory 103, then the data accessed must be added to an accumulator (e.g., 104 in FIG. 8) to provide the absolute amplitude information at each sample point prior to digital-to-analog conversion. Each of the sample points of the memory 103 may comprise a digital word of approximately 7 or 8 bits. The digital words thus read out from the memory 103 are supplied to the accumulator 104 which provides a digital representation of the waveform at selected sample points over a cycle of the waveform and at a frequency corresponding to the note to be reproduced. As above-described, this digital waveform representation may itself be operated upon for waveshape control, e.g., attack and decay, and subsequently is supplied to a digital-to-analog converter for producing an appropriate output wave, for example, as the sample point address source, such as audio speakers, of the organ.

Memory 103 may be a microminiature diode array of the type disclosed by R. M. Ashby et al. in U.S. Pat. No. 3,377,513, issued Apr. 9, 1968, and assigned to the same assignee as is the present invention. The array may, for example, contain an amplitude representation of the desired waveform in binary words (as each of 48 or more sample points. Such a capacity permits the storage of up to 128 amplitude levels in addition to a polarity (algebraic sign) bit. In any event, the capacity of memory 103 should be sufficient to allow faithful reproduction of note frequencies.

If whole values of amplitude levels at the sample points of the waveform are read from memory 103 in the embodiment of FIG. 8, the same sample point may be addressed several times in succession. This is the result of the requirement that the memory be accessed at a fixed rate for every note frequency, a requirement which implies that for decreasing note frequencies an increasing number of sample points must be read out during each cycle; and since the number of sample points is fixed and no sample points can be skipped regardless of note frequency, this simply means repetition of the same sample point possibly several times in succession. This does not undesirably affect the ultimate waveform generated, however, because there is consistent plural sampling of each point of the stored waveform.

On the other hand, if incremental values of the waveform have been stored in memory 103, each increment can be read out only once during each cycle of the waveform. This is because an accumulation of incremental values is required, and repetition would be significant. Accumulation and the ultimate waveform to be generated, regardless of the note frequency. Since the same sample point may be read out of memory 103 several times in succession depending upon the note frequency to be produced, just as in the whole value sample point case noted above, for incremental values all but one readout for each sample point must be inhibited to prevent repetitive increments. This does not undesirably affect the waveform, however, because there is consistent plural sampling of each point of the stored waveform.

As the note has been selected, the incremental values of the waveform may be read from memory 103 in the embodiment of FIG. 8, the same sample point may be addressed several times in succession. This is the result of the requirement that the memory be accessed at a fixed rate for every note frequency, a requirement which implies that for decreasing note frequencies an increasing number of sample points must be read out during each cycle; and since the number of sample points is fixed and no sample points can be skipped regardless of note frequency, this simply means repetition of the same sample point possibly several times in succession. This does not undesirably affect the ultimate waveform generated, however, because there is consistent plural sampling of each point of the stored waveform.

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abruptly when that key is released. At times, this may be a desirable effect to maintain during the play of a musical selection. In those cases, the attack and decay controls may be avoided entirely, or the scale factor supplied to multiplier 120, and with which the amplitude samples are to be multiplied, may be set at unity. More often, however, attack and/or decay are desirable for or in conjunction with special effects, such as percussion, sustain, and so forth.

The multiplying scale factor is varied as a function of time to correspondingly vary the magnitude of the digital samples, with which it is multiplied, on a progressive basis to simulate attack and/or decay. In the embodiment of FIG. 10, the total time duration and the time constant(s) for the attack or decay are controlled by a counter 122 which may be selectively supplied with uniformly timed pulses that are independent of the specific note frequency under consideration, such as pulses obtained or derived from the master clock, or with pulses having a repetition rate representative of or proportional to the note frequency. In this respect, the counter 122 may be considered as determining the abscissa of a graph of envelope amplitude versus time and representative of the attack or decay. The ordinate or amplitude scale of the graph is represented by the scale factors stored in the read-only memory 125 which may be accessed by the counter itself, or by an address decoder 126 which addresses the memory for readout of scale factors on the basis of each count (or timed, separated counts) of counter 122.

The counter may be of the reversible, up-down (forward-backward) type in which it is responsive to incoming pulses to count upwardly when its "up" (here, attack) terminal is activated or downwardly when its "down" (here, decay) terminal is activated. The attack mode of the overall control unit is entered when the associated tone generator is captured by a hitherto unclaimed note pulse in the multiplexed signal. The capture of a tone generator is accompanied by a signal indicative of a key having been depressed (see FIG. 7B), from the assignment logic, and it is this signal which initiates the attack count of counter 122. In particular, the first "key depressed" signal (and possibly the only one that occurs upon capture of a tone generator 28) is effective to produce a counter in the first stage of ring counter 128, thereby supplying a trigger signal from that stage to a monostable delay multivibrator 130 which is set to have an ON time (delay time) of sufficient duration to ensure that the attack is completed despite release of the key prior to the normal end of the attack interval. It has been found that a delay time equal to or greater than approximately the time occupied by seven cycles (i.e., seven periods) of the lowest frequency note is quite adequate for multivibrator 130 to ensure this positive attack. During that interval, the "up" control of counter 122 is activated by the quasi-stable state of multivibrator 130 and the counter continues to count incoming pulses until the multivibrator spontaneously returns to its stable state, or until the note envelope reaches the full desired intensity (magnitude), if earlier. This full intensity value may be preset into the attack/decay control logic or it may be determined by logic circuitry responsive to such factors as the force with which the respective key is struck (i.e., to velocity-responsive or touch-responsive device outputs). In the embodiment shown in FIG. 10, the former arrangement is utilized in which a maximum desired count is set into a fixed counter 131 for continuous comparison. In comparator 133 with the preset count of up-down counter 122. If the latter exceeds the former, a "disable" command is applied to the counter to terminate the attack.

Pulses to be counted by counter 122 may be obtained at a rate which is a function of note frequency, as by supplying the output of phase angle calculator 109 to a phase-to-frequency converter 135, or at a rate based on the master clock rate, whichever is desired. Selection of either rate is accomplished by appropriately setting a switch 136 coupled to an associated switch or key on or adjacent to one of the keyboards.

In operation of the attack/decay control unit of FIG. 10, after switch 136 has been set at the desired position, the pulses to be counted appear at the input of counter 122 but no count is initiated until a key is depressed and the associated pulse in the multiplexed signal from the keyboard results in the capture of a tone generator 28. The "key depressed" signal from the generator assignment logic initiates a count in ring counter 128, which had been reset by completion of decay the immediately preceding time the attack/decay control unit had been used. Preferably, the latter reset signal is obtained upon switching of the claim flip-flop 53 in the assignment logic 26 to the "not claimed" (decay complete) state. The up count of counter 122 is thereby enabled and continues through completion of attack regardless of whether or not the key remains depressed. If the count pulses are a function of note frequency, the duration of attack is based upon note frequency as well; otherwise, the positive attack interval is fixed regardless of note frequency.

With each count of counter 122 (or less frequently, by use of suitably timed "enabling" commands), address decoder 126 develops a related address for accessing the scale factor stored in the appropriate address of read-only memory unit 125, to be combined as a product in multiplier 120 with the amplitude samples being read from tone generator 28 of FIG. 8. By presetting memory unit 125 such that the scale factors stored therein are logarithmically increasing (up to the equivalent of unity) with addresses decoded according to progressively increasing count in counter 122 (up to the maximum desired count, representing full note intensity), a logarithmic attack is provided in the note being played. Furthermore, since the initial attack is positive, i.e., continues to completion regardless of the present condition of the key which was struck to produce the attack, the logarithmic rise at the leading edge of the note waveform continues smoothly to full intensity of the note.

When the key is released, a "key release" signal is applied from AND gate 62 of assignment logic 26 (FIG. 7B) to a flip-flop 138 to initiate the decay mode of the attack/decay control unit by enabling the "decay" (down) count of counter 122. Accordingly, incoming pulses to the counter are counted downwardly from the count representative of full intensity, until a zero count is obtained unless decay is terminated earlier. As in the case of the attack mode, the count in counter 122 is periodically decoded (e.g., once each count) by unit 126 for addressing of memory 125, thereby supplying logarithmically decreasing scale factors, from unity to zero, for multiplication with amplitude samples from the tone generator in multiplier 120. This produces the desired fall in note intensity at the trailing portion of the note waveform. Alternatively, to rely on zero count, scaler control logic may be implemented to signal completion of the decay mode.

If during decay the same note pulse should reappear in the multiplexed keyboard signal, indicating depression of the associated key virtually immediately after release thereof, a second "key depressed" signal is applied to ring counter 128 thus increasing the count therein to the second stage and switching flip-flop 138 from the decay state to its other stage, which reintroduces the attack mode. Since decay is incomplete in this particular instance, the count of counter 122 now proceeds upwardly from the minimum count which had been attained when decay was interrupted. If, however, the key is again released, prior to completion of attack, positive feedback is no longer in effect and the flip-flop 138 reverts immediately to the decay state by virtue of application of the "key release" signal thereto.

To prevent flip-flop 138 from being in the "decay" state when the initial attack condition is established in counter 122 (by the quasi-stable state of delay MV 130), flip-flop 138 may be switched to its "attack" state upon full completion of decay, by the "not claimed" signal of flip-flop 53 in the assignment logic unit which produced capture of the associated tone generator. Concurrent operation of flip-flop 138 in the "attack" state and MV 130 in the quasi-stable state will not affect
the above-described operation of the attack/decay control unit.

Upon completion of decay of a note whose representative pulse in the keyboard multiplexed signal resulted in capture of a tone generator, a "decay complete" signal is applied to the claim flip-flop 53 (FIG. 7B) of the respective assignment logic unit to cause that flip-flop to return to its "not claimed" state, and thereby to release the tone generator for claiming by another note. The "decay complete" signal may be supplied by the zero count of counter 122 or by any conventional detector for sensing the absence of further output from multiplier 120.

We claim:
1. In an electronic musical instrument, the combination comprising:
   means for storing digital samples of a waveform,
   a plurality of switches associated with notes of the musical scale and selectively operable to call forth the related notes,
   means responsive to actuation of each of said switches for reading out selected ones of said digital samples from said storing means at a rate to produce said waveform at the related note frequency,
   means for storing a plurality of predetermined scale factors corresponding to desired attack and decay effects, means defining a succession of time periods over a time interval corresponding to a desired rate of attack and decay,
   further means responsive to actuation and release of each of said switches and to said time interval defining means for addressing said scale factor storing means in said succession of time periods over said time interval to derive therefrom a corresponding succession of selected ones of said predetermined scale factors, and
   means for combining said selected digital samples read from said digital sample storing means with said predetermined attack and decay scale factor means derived from said scale factor storing means over said time interval upon actuation and release of each of said switches to simulate attack and decay, respectively, of the waveform at the related note frequency.

2. The combination according to claim 1 wherein said combining means comprises a multiplier, said multiplier receiving said scale factors in succession from said scale factor storing means and said digital samples from said digital sample storing means and effecting a multiplication thereof to produce a succession of weighted digital samples at the related note frequency simulating attack and decay, respectively of the waveform over the predetermined time interval.

3. The combination according to claim 1 wherein there is further provided means responsive to initial actuation of a switch to initiate and maintain the attack effect by said combining means for the duration of said time interval regardless of subsequent deactuation of that switch during the said time interval of attack.

4. The combination according to claim 3 wherein there is further provided means responsive to subsequent actuation of the last-named switch during decay of the waveform in said time interval of decay for reinitiating the attack.

5. The combination according to claim 1 wherein said scale factor storing means comprises a read-only memory containing a plurality of digital scale factors for scaling the amplitude of said stored digital samples read from said digital sample storing means.

6. The combination according to claim 1 wherein said weighting means includes means for selectively establishing the time interval of the attack or the decay.

7. The combination according to claim 6 wherein said time interval establishing means is responsive to the frequency of the note associated with the actuated switch to establish the duration of the time interval in relation to the frequency of the selected note.

8. The combination according to claim 6 wherein said time interval establishing means is responsive to a fixed time reference to establish the duration of the time interval of attack or decay, independent of the frequency of the selected note.

9. An electronic musical instrument, comprising:
   a plurality of keys individually actuatable to cause the production of sounds corresponding to related notes of the musical scale, and deactuable to cause the cessation of the respective sounds,
   means for sequentially and repetitively scanning said keys to detect the actuation or deactuation of any one or more thereof,
   means responsive to actuation of one or more of said keys as detected by said scanning means to generate a digital signal containing assignments of the notes associated with the respective actuated keys, and responsive to deactuation of a key for removing the respective note assignment, means for storing digital samples of a waveform of a musical note, means responsive to note assignments in said digital signal for selectively retrieving digital samples of said waveform from said storing means at a rate to produce said waveform at the corresponding note frequencies, and
   attack and decay control means selectively responsive to the initiation and removal of note assignments in said digital signal for correspondingly weighting the samples appearing at the beginning and end of the note waveform envelope to effect attack and decay of the note in accordance with the actuation and deactuation, respectively, of the key.

10. The instrument according to claim 9 wherein said attack and decay controlling means further includes means for selecting the time of the attack and the decay.

11. The instrument according to claim 10 wherein said duration-selecting means sets the duration as a function of the frequency of the selected note.

12. The instrument according to claim 10 wherein said duration-selecting means sets the duration as a fixed time interval independent of the frequency of the selected note.

13. A digital electronic musical instrument having switches selectively operable to bring forth respective notes of the musical scale, comprising:
   means assigning each of said switches to a distinct and different time slot in a sequence of cyclically repeated time slots of a digital signal,
   means responsive to selective operation of a switch to provide a signal representative of such operation of said switch in the respective assigned time slot for that switch in each cycle of repetition of said sequence of time slots during which said switch is operated, controllable tone generating means for producing a digital representation of a waveform at a selectable frequency, means synchronized with said cyclically repeating sequence of time slots to which said switches are assigned and responsive to a signal appearing in any time slot for controlling said tone generating means to produce said digital waveform representation at a frequency corresponding to the frequency of the respective note for that time slot, and
   attack and decay control means selectively responsive to the initiation and removal of note assignments in said digital signal for correspondingly weighting the samples appearing at the beginning and end of the note waveform envelope to effect attack and decay of the note in accordance with the actuation and deactuation, respectively, of the key.

14. The instrument defined by claim 13 wherein said attack and decay control means comprises:
   means for storing a plurality of scale factors,
   means responsive to the appearance or removal of a signal in each time slot for selective accessing of said scale factor storing means to derive corresponding, selected scale
3,610,805

factors therefrom over a desired time interval of attack and decay, respectively, and means for weighting said digital samples with said scale factors to vary the magnitudes of selected portions of said digital waveform representation in synchronism with the production thereof from said tone generating means.

15. The instrument defined by claim 13 wherein said attack and decay means comprises means for maintaining the attack for the duration of the attack time interval regardless of release of a switch prior to completion of that attack time interval.

16. A system for simulating attack and decay of notes generated by an electronic musical instrument, comprising:

means responsive to actuation of a key for producing an electrical representation of a note to be produced at the corresponding frequency and for maintaining that representation in a sustain mode during continuous actuation of the key,

means defining a succession of time periods wherein each period is not substantially longer in duration than the period of the lowest note frequency to be produced,

means for establishing a predetermined number of successive time periods for defining desired time intervals of attack and decay,

means for storing a plurality of scale factors,

means responsive to initial actuation and subsequent release of a key and to said time period defining means to effect selective addressing of said scale factor storing means in successive time periods to derive therefrom a succession of scale factors over said time intervals of attack and decay, respectively,

means for combining each said electrical representation with the succession of said scale factors thus derived upon initial actuation of a key to effect attack of the note produced over said time interval of attack prior to the sustain mode thereof, and

means for maintaining the electrical representation of the note for said time interval of decay following release of the corresponding key, said combining means combining the succession of scale factors with said electrical representation of said time interval of decay to produce a decay of the note following the sustain mode thereof.

17. A system as recited in claim 16 wherein said time interval defining means comprises:

means for counting said time periods,

means for storing a predetermined count in accordance with the duration of each said time period for defining the desired time intervals of attack and decay, and

comparison means for comparing the count of said time periods with said predetermined count for terminating further attack and decay of each note when said counts are equal.

18. A system as recited in claim 17 wherein said counting means is responsive to a fixed clock frequency for defining said time periods.

19. A system as recited in claim 17 wherein said counting means is responsive to the frequency of the note to be produced to define each said time period in accordance with the time period of that note frequency.

20. A system as recited in claim 16 wherein there is further provided means responsive to a successive actuation of a key during the time interval of decay of the corresponding note continuing form a prior actuation of that key to reinitiate the attack mode for that note.

21. A system as recited in claim 16 wherein there is further provided means for maintaining the electrical representation of a note for the time interval of attack despite release of the corresponding key within that time interval.

22. A system as recited in claim 16 wherein said electronic musical instrument comprises an electronic organ and

said time interval defining means and said scale factors stored in said scale factor memory are selected to simulate attack and decay effects of a pipe organ.
UNITED STATES PATENT OFFICE
Certificate of Correction

Patent No. 3,610,805

George A. Watson et al.

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below.

In the grant (only) insert Columns 13, 14, 15 and 16:
of the note to be generated. A set of next successive less significant bits may therefore specify the sample point address in accordance with the function of the decoder 103a. The more significant bits of the register 102 may be used to count numbers of cycles of the waveform for various control functions not here pertinent. In addition, by selecting appropriate bit positions by means of decoder 103a, the frequency of the note reproduced may be readily adjusted to different octaves. That is, a 1-bit positional shift constitutes division or multiplication by two, depending upon direction of shift. For example, if the most significant bit is numbered 1 and thus bit positions 2 through 6 comprise the sample point address bits normally used for an 8 foot voice, then a 16 foot voice can be obtained by using bits 1 through 5 as the sample point address source. Correspondingly, a 4 foot voice can be obtained by using bits 3 through 7 as the sample point address bits.

The read-only memory 103 contains digital amplitude values of a single cycle of the complex periodic waveform to be reproduced for all note frequencies. That is to say, the same complex periodic waveform is to be reproduced for each note played, the only difference being the frequency at which the complex waveform is reproduced.

Referring to FIG. 9, illustrating a typical complex waveshape 110 of the type that may be produced by a pipe organ, the sample points may be sampled at a multiplicity of points, shown as vertical lines in the Figure, to provide the amplitude data for storage in memory 103. If absolute amplitude data is stored in memory 103, then the data accessed is the actual amplitude of the output waveform at the respective sample points (i.e., with respect to a "zero" level at time axis 111). In that event, the digital amplitude data successively read from the memory may be applied directly to an appropriate digital-to-analog conversion system. On the other hand, if incremental amplitude information (i.e., simply the difference in amplitude between the present sample and the immediately preceding sample) is stored in memory 103, then the data accessed must be added to an accumulator (e.g., 104 in FIG. 8) to provide the absolute amplitude information at each sample point prior to digital-to-analog conversion. Each of the sample points of the memory 103 may comprise a digital word of approximately 7 or 8 bits.

The digital words thus read out from the memory 103 are supplied to the accumulator 104 which provides a digital representation of the waveform at selected sample points over a cycle of the waveform and at a frequency corresponding to the note to be reproduced. As before described, this digital waveform representation may itself be operated upon for waveshape control, e.g., attack and decay, and subsequently is supplied to a digital-to-analog converter for producing an analog signal suitable for driving the acoustical output means, such as audio speakers, of the organ.

Memory 103 may be a microcircuit diode array of the type disclosed by R. M. Ashby et al. in U.S. Pat. No. 3,377,513, issued Apr. 9, 1968, and assigned to the same assignee as is the present invention. The array may, for example, contain an amplitude representation of the desired waveform in the form of an 8-bit binary word at each of 48 or more sample points. Such a capacity permits the storage of up to 128 amplitude levels in addition to a polarity (algebraic sign) bit. In any event, the capacity of memory 103 should be sufficient to allow faithful reproduction of note frequencies.

If whole values of amplitude levels at the sample points of the waveform are read from memory 103 in the embodiment of FIG. 8, the same sample point may be addressed several times in succession. This is the result of the requirement that the memory be addressed at a fixed rate for every note frequency, a requirement which implies that for decreasing note frequency an increasing number of sample points must be read out during each cycle; and since the number of sample points is fixed and no sample points can be skipped regardless of note frequency, this simply means repetition of the same sample point possibly several times in succession. This does not constitute after the ultimate waveform produced, however, because there is consistent sampling of each point of the stored waveform.

On the other hand, if incremental values of the waveform have been stored in memory 103, each increment can be read out only once during each cycle of the waveform. This is because an accumulation of incremental values is required, and repetition will produce a significant error in the accumulation and the ultimate waveform to be generated, regardless of the note frequency. Since the same sample point may be read out of memory 103 several times in succession depending upon the note frequency to be produced, just as in the whole value sample point case noted above, for incremental values all but one readout for each sample point must be inhibited to prevent repetitive application to accumulator 104. To that end, a gate 103b (shown dotted in FIG. 8) is positioned in the output line of memory 103 preceding accumulator 104 if incremental values are utilized. Gate 103b is preferably enabled to pass the sample value being read from the memory only when the least significant bit in address register 102 changes.

Since such change occurs upon a "carry" into that position, indicating advancement to the next memory address, a bit change sensor 102a may be used to detect the change and to enable gate 103b at each advancement to a new address. The same sample point may still be accessed several times in succession, but only one such value will be "read out" (i.e., will be passed by the gate since it is disabled at all other times).

The phase angle calculations should be such that the highest note playable is that note for which a sample point is read out each time the memory time is advanced. Since the ratio between adjacent notes on the equally tempered musical scale is an irrational number, it is preferable that the largest number in the phase angle register be slightly smaller than the least significant bit in the address register. If the phase angle number were larger, it would be necessary to occasionally skip a sample point and this would lead to inconsistency in the note frequency, whereas if the phase angle number were equal to the least significant bit in the address register the note frequency would be slightly higher (i.e., about one-half of a halftone higher) than the highest note that can be played. By requiring the phase angle number to be slightly smaller, the highest note capability of the instrument will not be exceeded.

The same read-only memory 103 may be shared by all of the tone generators 28 if the data words (amplitude values of sample points) read therefrom are gated to respective waveshapers in synchronism with the addressing of the memory for the respective notes being played. In other words, simultaneous or concurrent play of two or more notes requires that these be distinguished as separate sets of sample points, if a single memory is to be shared for all tone generators.

In the present embodiment, however, it is assumed that each tone generator has its own memory (and, incidentally, memories composed of microcircuit diode arrays of the type disclosed in the aforementioned Ashby et al. patent are readily fabricated with more than 5,000 diode elements per square inch), which supplies its digital output to a respectively associated attack and decay control unit. The binary-valued amplitude samples are applied directly to the attack and decay circuitry if each sample is a whole value, or may be applied via an accumulator 104 if each sample is an incremental value. Alternatively, accumulation of incremental values may be performed after shaping, if desired.

Referring to FIG. 10, an embodiment of the attack and decay unit associated with each tone generator includes a multiplier 120 to which the sample values from memory 103 are applied for multiplication by an appropriate scale factor to control the leading and trailing portions of the note waveform envelope. As is well known, the faithful simulation of true pipe organ sounds by an electronic organ requires that the latter be provided with the capability to shape each note to produce other than an abrupt rise and fall. Without special attack and decay control, the note waveform produced by an electronic organ normally rises sharply to full intensity immediately upon depression of the respective key, and ceases
abruptly when that key is released. At times, this may be a desirable effect to maintain during the play of a musical selection. In those cases, the attack and decay controls may be avoided entirely, or the scale factor supplied to multiplier 120 and with which key. In some samples are to be multiplied. More often, however, attack and/or decay are desirable for in conjunction with special effects, such as percussion, sustain, and so forth. The multiplying scale factor is varied as a function of time to correspondingly vary the magnitude of the digital samples, with which it is multiplied, on a progressive basis to simulate the attack and/or decay. In the embodiment of FIG. 10, the total time duration and the time constant(s) for the attack or decay are controlled by a counter 122 which may be selectively supplied with uniformly timed pulses that are independent of the specific note frequency under consideration, such as pulses obtained or derived from the master clock, or with pulses having a repetition rate representative of or proportional to the note frequency. In this respect, the counter 122 may be considered as determining the absissa of a graph of envelope amplitude versus time and representative of the attack or decay. The ordinate or amplitude scale of the graph is represented by the series of scale factors stored in a read-only memory 125 to be accessed by the counter itself, or by an address decoder 126 which addresses the memory for readout of scale factors on the basis of each count (or timed, separated counts) of counter 122. The counter may be of the reversible, up-down (forward-backward) type in which it is responsive to incoming pulses to count upwardly when its “up” (here, attack) terminal is activated, and to count downwardly when its “down” (here, decay) terminal is activated. The attack mode of the overall control unit is entered when the associated tone generator is captured by a hitherto unclaimed note pulse in the multiplexed signal. The capture of a tone generator is accompanied by a signal indicative of a key having been depressed (see FIG. 7B), from the assignment logic, and it is this signal which initiates the attack count of counter 122. In particular, the first “key depressed” signal (and possibly the only one) that occurs upon capture of a tone generator 28 is effective to produce a count in the first stage of ring counter 128, thereby supplying a trigger signal from that stage to a monostable delay multivibrator 130 which is set to have an ON time (delay time) of sufficient duration to ensure that the attack is completed despite release of the key prior to the normal end of the delay. It has been found that a delay time equal to or greater than approximately the time occupied by seven cycles (i.e., seven periods) of the lowest frequency note is quite adequate for multivibrator 130 to ensure this positive attack. During that interval, the “up” control of counter 122 is activated by the quasi-stable state of multivibrator 130 and the counter continues to count incoming pulses until the multivibrator spontaneously returns to its stable state, or until the note envelope reaches the full desired intensity (magnitude), if earlier. This full intensity value may be preset into the attack/decay control logic or it may be determined by logic circuitry responsive to such factors as the force with which the respective key is struck (i.e., to velocity-responsive or touch-responsive device outputs). In the embodiment shown in FIG. 10, the former arrangement is utilized in which a maximum desired count is set into a fixed counter 131 for continuous comparison in comparator 133 with the preset count of up-down counter 122. If the latter exceeds the former, a “disable” command is applied to the counter to terminate the attack. Pulses to be counted by counter 122 may be obtained at a rate which is a function of note frequency, as by supplying the output of phase angle calculator 100 to a phase-to-frequency converter 135, or at a rate based on the master clock rate, whichever is desired. Selection of the rate is accomplished by appropriately setting a switch 136 coupled to an associated switch or keyboard adjacent to one of the keyboards. In operation of the attack/decay control unit of FIG. 10, after switch 136 has been set at the desired position, the pulses to be counted appear at the input of counter 122 but no count is initiated until a key is depressed. The multiplexed signal from the keyboard results in the capture of a tone generator 28. The “key depressed” signal from the generator assignment logic initiates a count in ring counter 128, which had been reset by completion of decay the immediately preceding time the attack/decay control unit had been used. Preferably, the latter reset signal is obtained upon switching of the claim flip-flop 53 in the assignment logic 26 to the “not claimed” (decay complete) state. The up count of counter 122 is thereby enabled and continues through completion of attack regardless of whether or not the key remains depressed. If the count pulses are a function of note frequency as well, otherwise, the positive attack interval is fixed regardless of note frequency. With each count of counter 122 (or less frequently, by use of suitably timed “enabling” commands), address decoder 126 develops a related address code for accessing a digital scale factor stored in the appropriate address of read-only memory unit 125, to be combined as a product in multiplier 120 with the amplitude samples being read from tone generator 28 of FIG. 8. By presetting memory 125 such that the scale factors stored therein are logarithmically increasing (up to the equivalent of unity) with addresses decoded according to progressively increasing count in counter 122 (up to the maximum desired count, representing full note intensity), a logarithmic attack is provided in the note being played. Furthermore, since the initial attack is positive, i.e., continues to completion regardless of the present condition of the key which was struck to produce the attack, the logarithmic rise at the leading edge of the note waveform continues smoothly to full intensity of the note. When the key is released, a “key release” signal is applied from AND gate 62 of assignment logic 26 (FIG. 7B) to a flip-flop 138 to initiate the decay mode of the attack/decay control unit by enabling the “decay” (down) count of counter 122. Accordingly, incoming pulses to the counter are counted downwardly from the count representative of full intensity, until a zero count is obtained unless decay is terminated earlier. As in the case of the attack mode, the count in counter 122 is periodically decoded (e.g., once each count) by unit 126 for addressing of memory 125, thereby supplying logarithmically decreasing scale factors, from unity to zero for multiplication with amplitude samples from the tone generator in multiplier 120. This produces the desired fall in note intensity at the trailing portion of the note waveform. Alternatively to relying on zero count, scaler control logic may be implemented to signal completion of the decay mode. If during decay the same note pulse should reappear in the Normally a keyboard signal, indicating depression of the associated key virtually immediately after release thereof, a second “key depressed” signal is applied to ring counter 128 thus increasing the count therein to the second stage and switching flip-flop 138 from the decay state to its other state, which reintroduces the attack mode. Since decay is in complete in this particular instance, the count of counter 122 now proceeds upward from the minimum count which had been attained when decay was interrupted. If, however, the key is again released, prior to completion of attack, positive attack is no longer in effect and the flip-flop 138 is reversed immediately to the decay state by virtue of application of the “key release” signal thereto.

To prevent flip-flop 138 from being in the “decay” state when the initial attack condition is established in counter 122 (by the quasi-stable state of delay MV 130), flip-flop 138 may be switched to its “attack” state upon full completion of decay, by the “not claimed” signal of flip-flop 53 in the assignment logic unit which produced capture of the associated tone generator. Concurrent operation of flip-flop 138 in the “attack” state and MV 130 in the quasi-stable state will not affect
Signed and sealed this 16th day of May 1972.

[seal]

Attest:

EDWARD M. FLETCHER, JR.,
Attesting Officer.

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