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Deutsch

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[45] May 7, 1974

[54] PRODUCTION OF CELESTE IN A COMPUTOR ORGAN

[75] Inventor: **Ralph Deutsch,** Sherman Oaks, Calif.

[73] Assignee: **Nippon Gakki Seizo Kabushiki Kaisha,** Hamamatsu, Japan

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[51] **Int. Cl.** **G10h 1/02,** G10h 5/02
[58] **Field of Search** .... 84/1.01, 1.03, 1.22–1.24, 84/DIG. 4, DIG. 5

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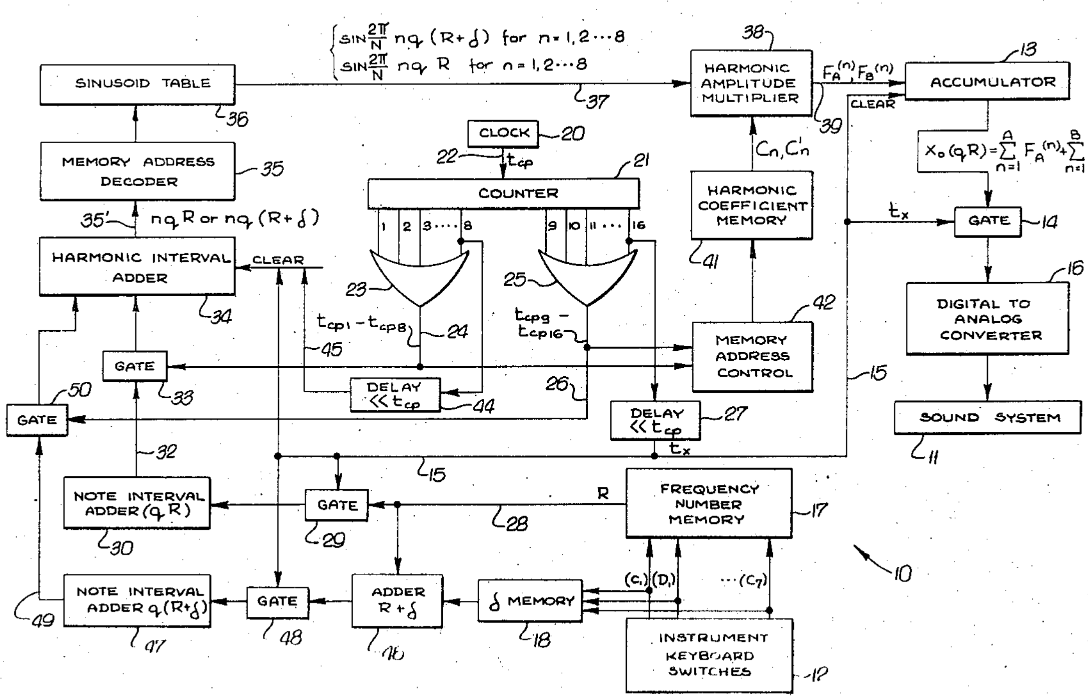
Primary Examiner—Richard B. Wilkinson
Assistant Examiner—Stanley J. Witkowski
Attorney, Agent, or Firm—Howard A. Silber; Flam& Flam

[57] **ABSTRACT**

Apparatus is disclosed for producing a celeste effect in a computor organ of the type wherein musical notes are generated by computing the amplitudes at successive sample points of a musical waveshape and converting the amplitudes to notes as the computations are carried out in real time. Each amplitude is computed during a regular time interval t_x by individually calculating and combining at least two sets of discrete Fourier components. The first set includes harmonically related components, generally the true pitch fundamental and overtones of each selected note. Components of the second set are offset slightly higher in frequency from those in the first set. The resultant synthesized sound resembles an organ celeste stop wherein two organ pipes, one tuned slightly sharp with respect to the other, are sounded when a note is played.

In one illustrative embodiment, each set contains the same number of components, each component in the second set being slightly higher in frequency than the corresponding component of the first set. In another embodiment, the first set includes plural harmonic components, the second set contains only one component slightly offset from the fundamental of the first set.

16 Claims, 6 Drawing Figures



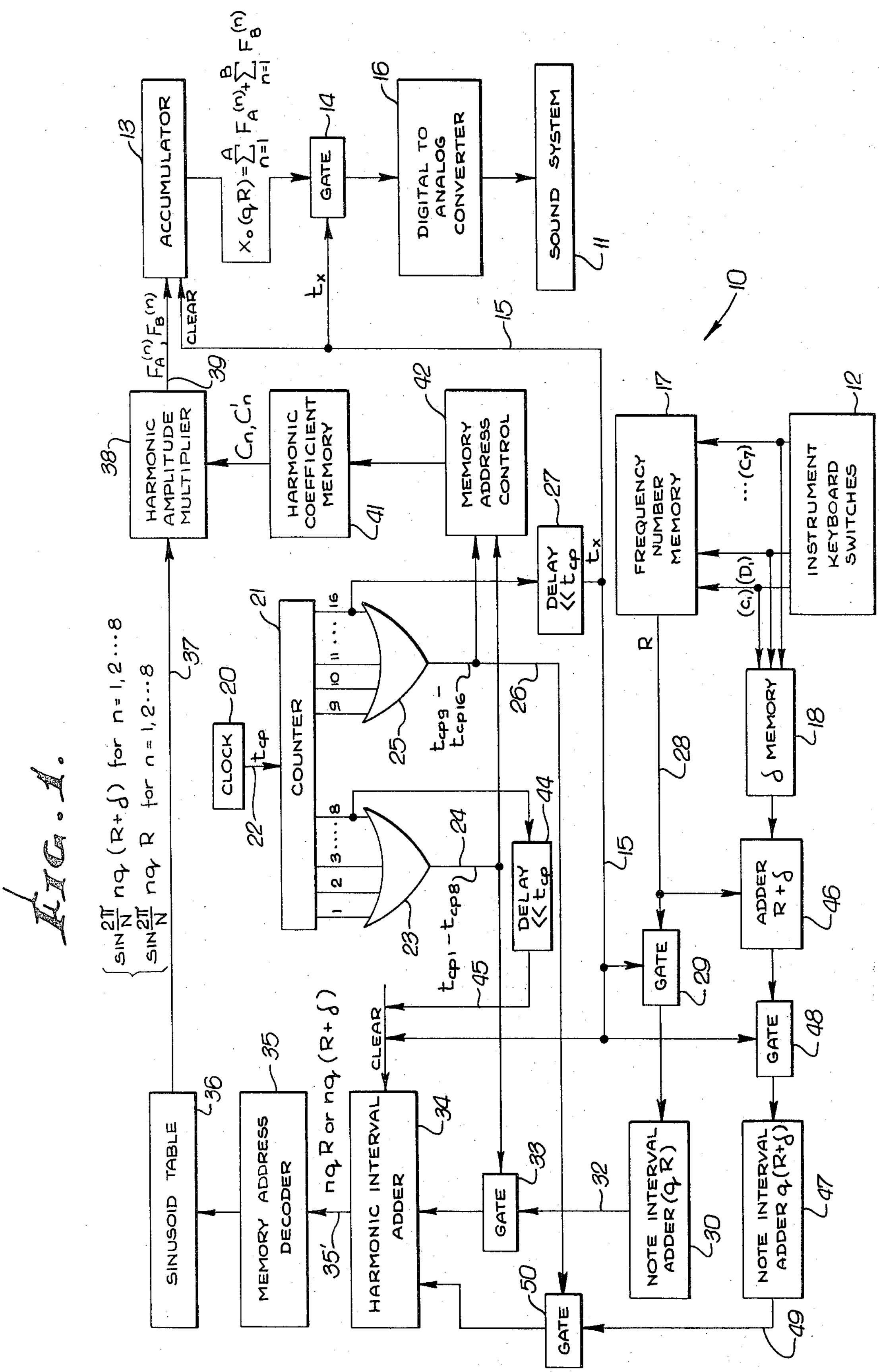


FIG. 1.
ACCUMULATOR
GATE
DIGITAL TO ANALOG CONVERTER
SOUND SYSTEM
HARMONIC AMPLITUDE MULTIPLIER
HARMONIC COEFFICIENT MEMORY
MEMORY ADDRESS CONTROL
DELAY << tcp
FREQUENCY NUMBER MEMORY
INSTRUMENT KEYBOARD SWITCHES
CLOCK
COUNTER
δ MEMORY
ADDER R+δ
CLEAR
SINUSOID TABLE
MEMORY ADDRESS DECODER
HARMONIC INTERVAL ADDER
NOTE INTERVAL ADDER (qR)
NOTE INTERVAL ADDER q(R+δ)
nqR or nq(R+δ)
R
tx
tcp
Cn, C'n

FIG. 4.

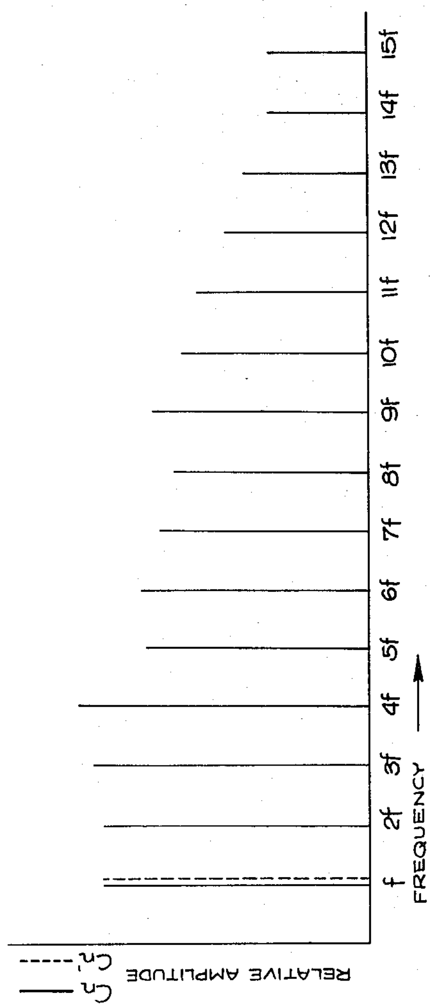


FIG. 2.

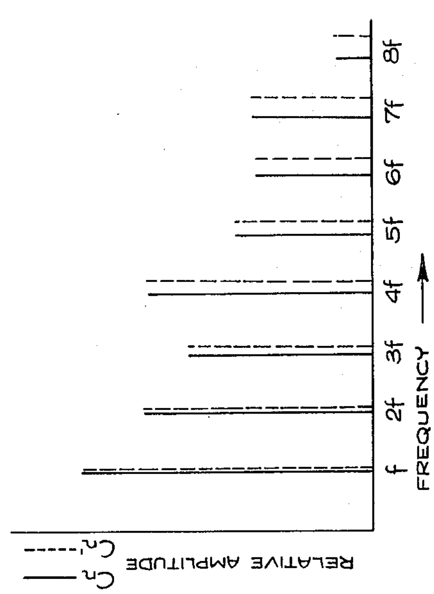


FIG. 5.

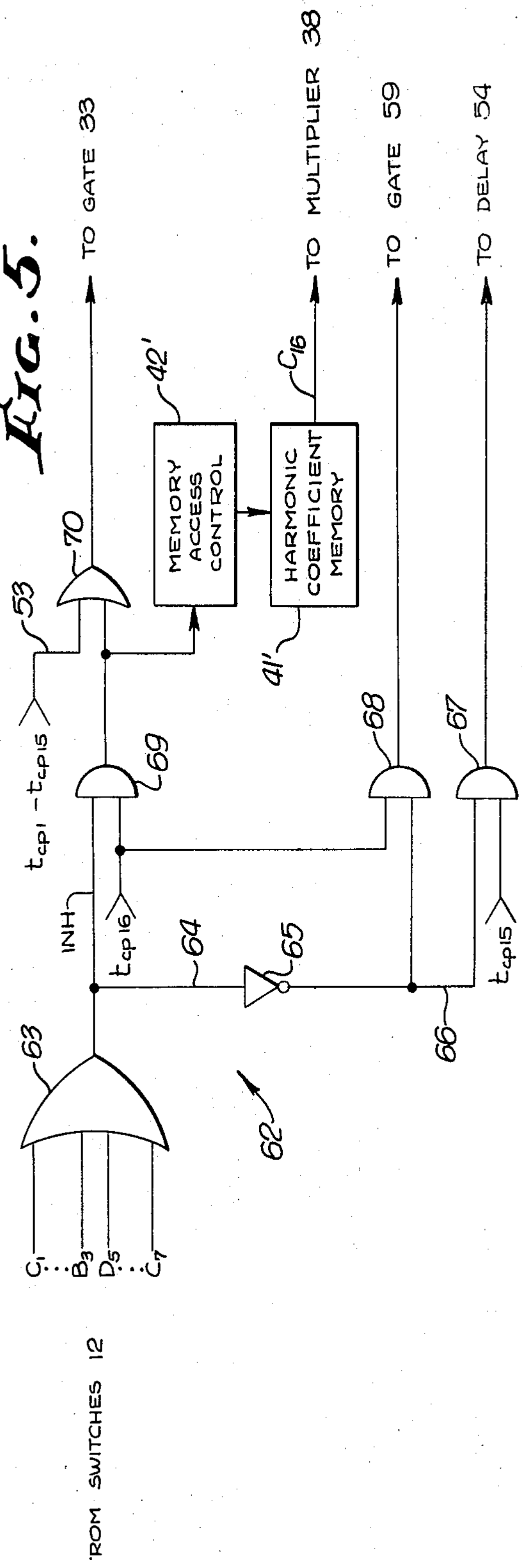


FIG. 3.

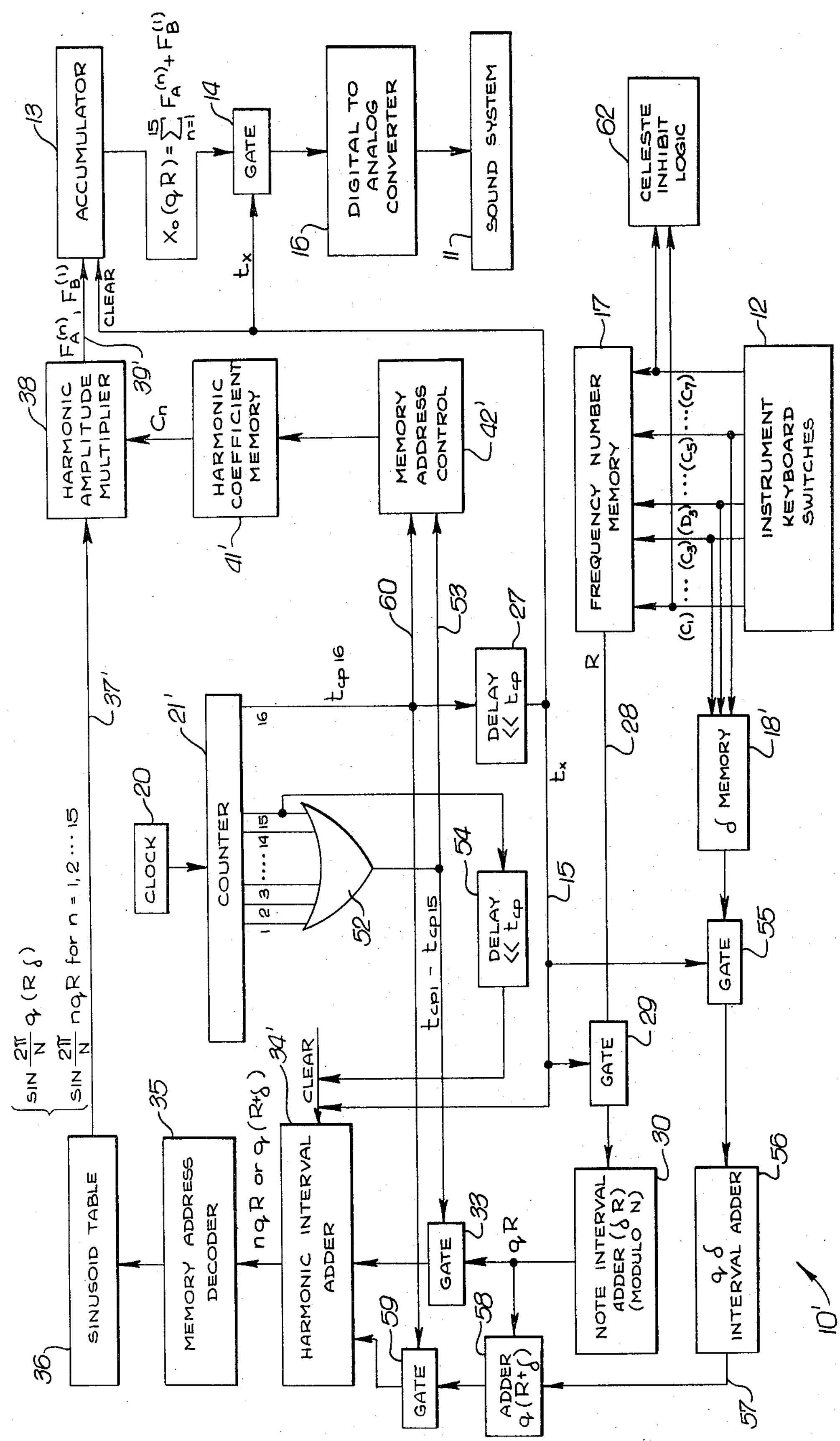
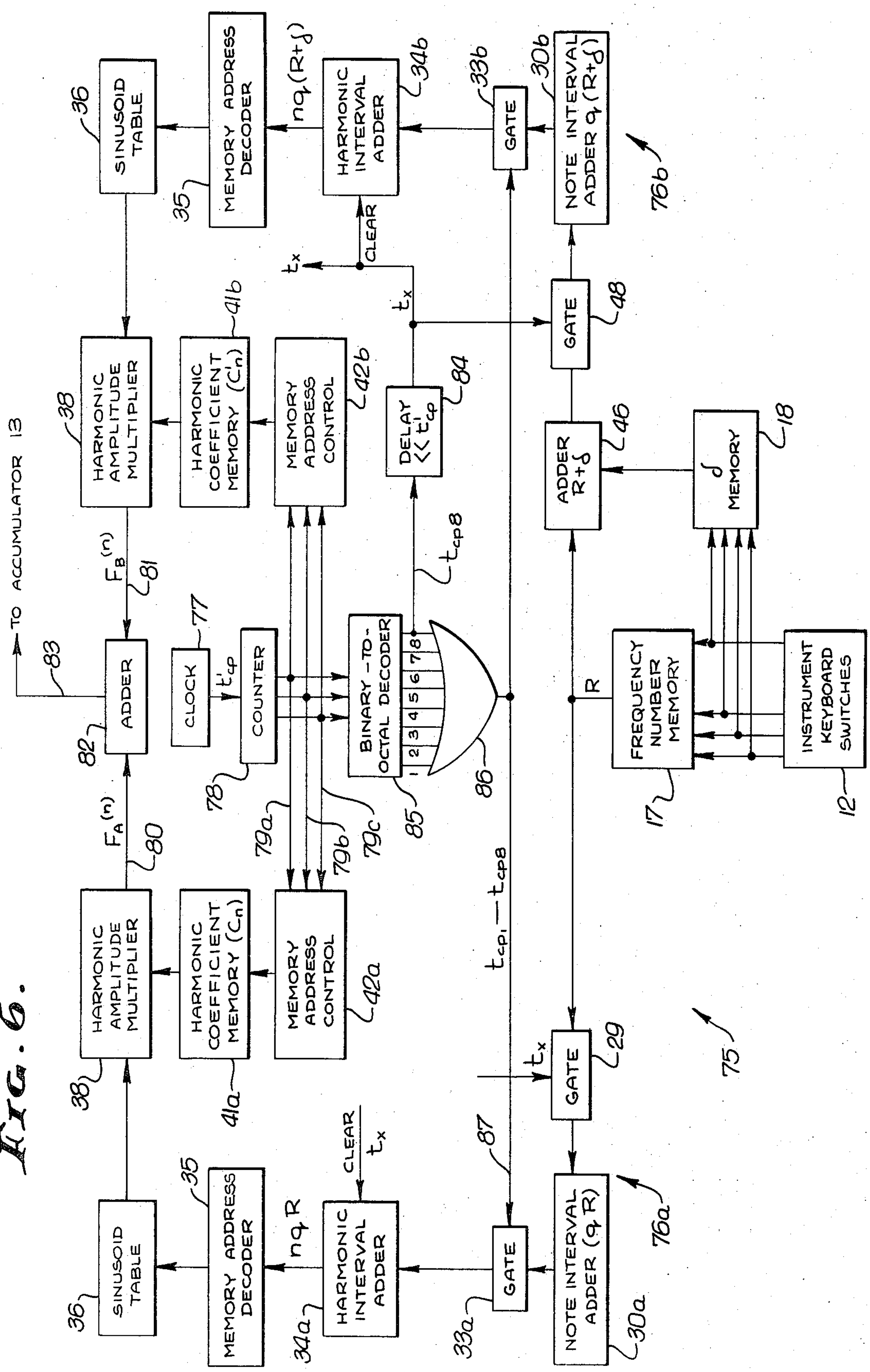

ACCUMULATOR
13
$X_o(qR) = \sum_{n=1}^{15} F_A^{(n)} + F_B^{(1)}$
14
GATE
DIGITAL TO ANALOG CONVERTER
16
SOUND SYSTEM
11
CELESTE INHIBIT LOGIC
62
$F_A^{(n)}, F_B^{(1)}$
CLEAR
t_x
39'
HARMONIC AMPLITUDE MULTIPLIER
38
C_n
HARMONIC COEFFICIENT MEMORY
41'
MEMORY ADDRESS CONTROL
42'
FREQUENCY NUMBER MEMORY
17
INSTRUMENT KEYBOARD SWITCHES
12
$(C_1) \cdots (C_3)(D_3) \cdots (C_5) \cdots (C_7)$
R
60
53
27
DELAY $\ll t_{cp}$
t_{cp16}
21'
COUNTER
16
CLOCK
20
1 2 3 .... 14 15
52
54
DELAY $\ll t_{cp}$
$t_{cp1} - t_{cp15}$
15
t_x
28
δ MEMORY
18'
GATE
55
GATE
29
37'
$\sin \frac{2\pi}{N} q(R\delta)$
$\sin \frac{2\pi}{N} nqR$ for n = 1, 2 ⋯ 15
SINUSOID TABLE
36
MEMORY ADDRESS DECODER
35
nqR or $q(R+\delta)$
34'
CLEAR
HARMONIC INTERVAL ADDER
GATE
33
qR
NOTE INTERVAL ADDER (δ R) (MODULO N)
30
$q\delta$ INTERVAL ADDER
56
57
ADDER $q(R+\delta)$
58
GATE
59
10'

FIG. 6.


SINUSOID TABLE
MEMORY ADDRESS DECODER
HARMONIC INTERVAL ADDER
GATE
NOTE INTERVAL ADDER q(R+δ)
nq(R+δ)
HARMONIC AMPLITUDE MULTIPLIER
HARMONIC COEFFICIENT MEMORY (C'n)
MEMORY ADDRESS CONTROL
DELAY << t'cp
ADDER R+δ
δ MEMORY
CLEAR
tx
tcp8
TO ACCUMULATOR 13
ADDER
CLOCK
t'cp
COUNTER
BINARY-TO-OCTAL DECODER
1 2 3 4 5 6 7 8
FREQUENCY NUMBER MEMORY
INSTRUMENT KEYBOARD SWITCHES
R
HARMONIC COEFFICIENT MEMORY (Cn)
tcp1 — tcp8
NOTE INTERVAL ADDER (qR)
nqR
36
35
34b
33b
30b
76b
41b
42b
84
48
46
18
38
81
83
82
77
78
79a
79b
79c
85
86
17
12
80
42a
41a
29
75
87
76a
34a
33a
30a

PRODUCTION OF CELESTE IN A COMPUTOR ORGAN

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to production of celeste in a computor organ.

2. Related Applications

The present invention is related to the inventor's copending U.S. Pat. applications No. 225,883, filed on Feb. 14, 1972, entitled COMPUTOR ORGAN and No. 298,365, filed on Oct. 17, 1972, entitled COMPUTOR ORGAN USING PARALLEL PROCESSING. Those disclosures are incorporated herein by reference.

3. Description of the Prior Art.

The celeste tones of a pipe organ are produced by a multi-rank set of pipes. One rank is set to true pitch, producing tones at the nominally correct 8-foot frequencies. The second rank consists of like sounding pipes, but tuned sharp with respect to true pitch. The frequency offset of the second rank is not consistent over the manual, but typically ranges from about 2 Hz at C_3 (the note of C in the third octave) to about 4 Hz at C_5. When a note is played, the listener perceives a pleasant beat note as the sounds from the two ranks interact. This gives the tone a considerable warmth.

In conventional electronic organs a celeste effect is obtained using a separate set of oscillators tuned sharp with respect to the usual analog tone generators. When mixed electrically or acoustically, the combined generator output produce a reasonable semblance of celeste. In another approach, a pseudo-celeste effect is achieved acoustically by using a slowly rotating speaker to reproduce the organ tones.

Celeste cannot easily be produced in a digital organ of the type wherein a stored musical waveshape is repeatedly read from memory at a rate determined by the fundamental frequency of the note being generated. (An instrument of this type is shown in the inventor's U.S. Pat. No. 3,515,792 entitled DIGITAL ORGAN.) A fundamental characteristic of celeste is an interference or beat effect which occurs between sounds of slightly different frequencies. To synthesize this effect requires production of a waveshape which changes in time. To achieve such synthesis in a system which repeatedly reproduces the same stored wave form requires two separate digital organs, one generating a note of true pitch, the other producing a note of slightly higher pitch. The two notes are combined, either electrically or acoustically, to produce celeste. Obviously, such implementation may double the system cost.

The principal object of the present invention is to produce a celeste effect in a computor organ of the type wherein musical notes are generated by individually calculating and combining the Fourier components comprising that note. To accomplish this, at least two sets of Fourier components, offset slightly in frequency from each other, are calculated and combined to synthesize each celeste tone. In effect, this corresponds to generating two notes, one at the true pitch and another tuned sharp. The resultant waveshape is not uniformly repititious, but changes in time; it may be thought of as the superposition of separate waveshapes associated with two notes of slightly different frequency. When this resultant waveshape is reproduced acoustically, a remarkably realistic celeste effect results.

SUMMARY OF THE INVENTION

As described in the above mentioned patent application entitled COMPUTOR ORGAN, musical notes are produced by computing in real time the amplitudes at successive sample points of a musical waveshape, and converting these amplitudes to notes as the computations are carried out. In accordance with the present invention, the amplitude at each sample point is obtained by summing at least two sets of Fourier components, one associated with the true pitch of the selected note, the other set being offset, generally slightly higher in frequency therefrom. The two sets of Fourier components thus may be considered as synthesizing respectively the true pitch and tuned-sharp ranks of a pipe organ celeste stop.

In one typical implementation, described in conjunction with FIGS. **1** and **2** below, the first set of Fourier components includes the fundamental and second through eighth harmonics of the selected note. These true pitch components are illustrated by the solid lines in the spectrum of FIG. **2.** The second set of Fourier components includes a fundamental having a frequency slightly higher than that of the first set, and seven overtones harmonically related to this shifted fundamental, and hence all offset in frequency with respect to the first set. The offset or frequency-shifted components are indicated by broken lines in the spectra of FIG. **2.**

The circuitry of FIG. **1** calculates both the true-pitch and frequency-offset Fourier components during each computation time interval t_x. The components are summed to obtain the waveshape amplitude at the sample point currently being evaluated. The computations are repeated during successive time intervals t_x to generate a waveshape which when acoustically reproduced yields a realistic celeste sound. The use of two component sets each having eight harmonics is quite satisfactory to synthesize a flute or soft string voice.

In the alternative embodiment of FIG. **3**, a greater number of true pitch harmonics are generated, as indicated by the solid lines in the spectrum of FIG. **4.** A rich string voice can be synthesized. The celeste effect is produced by a single harmonic component (shown as a broken line in FIG. 4) having a frequency slightly higher than the true-pitch fundamental. The resultant offset celeste rank has a "sinusoidal" waveform tuned sharp with respect to the first rank.

BRIEF DESCRIPTION OF THE DRAWINGS

A detailed description of the invention will be made with reference to the accompanying drawings, wherein like numerals designate corresponding parts in the several figures.

FIG. **1** is an electrical block diagram of a computor organ configured to produce a celeste effect with an equal number of Fourier components in the true-pitch and offset-frequency sets.

FIG. **2** is a harmonic spectrum associated with the computor organ of FIG. **1.**

FIG. **3** is an electrical block diagram of a computor organ configured for production of celeste and wherein only a single frequency-shifted component is generated.

FIG. **4** is a harmonic spectrum associated with the computor organ of FIG. **3.**

FIG. 5 is a simplified electrical block diagram of circuitry useful in conjunction with the computor organ of FIG. 3 for inhibiting production of celeste for certain selected notes.

FIG. 6 is an electrical block diagram showing celeste generation in a parallel processing computor organ.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The following detailed description is of the best presently contemplated modes of carrying out the invention. This description is not to be taken in a limiting sense, but is made merely for the purpose of illustrating the general principles of the invention since the scope of the invention best is defined by the appended claims.

Structural and operational characteristics attributed to forms of the invention first described shall also be attributed to forms later described, unless such characteristics are obviously inapplicable or unless specific exception is made.

The computor organ **10** of FIG. **1** produces via a sound system **11** musical notes having a celeste quality. For each note selected by the keyboard switches **12**, the computor organ **10** computes the amplitudes at successive sample points of a waveshape characterizing the selected note. Each amplitude is obtained by calculating two sets of discrete Fourier components as illustrated in FIG. **2**.

Both sets of components are summed algebraically in an accumulator **13** which, at the end of each computation time interval t_x contains the amplitude for the current sample point. This amplitude is provided via a gate **14**, enabled by the t_x signal on a line **15**, to a digital-to-analog converter **16** which supplies to the sound system **11** a voltage corresponding to the waveshape amplitude just computed. Computation of the amplitude for the next sample point subsequently is initiated, so that the analog voltage supplied from the converter **16** comprises a musical waveshape generated in real time. The resultant sound, synthesized from true pitch and frequency-offset harmonic components, realistically simulates a multi-rank celeste tone.

The period of the computed waveshape, and hence the fundamental frequency of the generated note, is established by a frequency number R selected by the keyboard switches **12**. A set of such frequency numbers corresponding to the notes of the instrument is stored in a frequency number memory **17**. Each true pitch Fourier component $F_A^{(n)}$ is calculated in accordance with the following equation:

$$F_A^{(n)} = C_n \sin(2\pi/N)\, nqR \text{ for } q = 1, 2, 3 \qquad (1)$$

where R is the frequency number mentioned above, and $n = 1, 2, 3, \ldots A$ designates the Fourier component during evaluated. The value $n = 1$ corresponds to the fundamental, $n = 2$ to the second harmonic, $n = 3$ to the third harmonic, and so forth. The harmonic coefficient C_n specifies the relative amplitude of n^{th} Fourier component. The value of R designates each sample point of the waveshape being generated.

Similarly, each frequency-offset Fourier component $F_B^{(n)}$ is calculated in accordance with the following equation:

$$F_B^{(n)} = C_n' \sin(2\pi/N)\, nq\,(R + \delta) \text{ for } q = 1\ 2, 3 \qquad (2)$$

where again $n = 1, 2, 3, \ldots B$ designates which order Fourier component is being evaluated. The harmonic coefficient C_n' specifies the relative amplitude of the n^{th} Fourier component in the shifted-frequency set. The value δ determines the extent of frequency-offset with respect to the corresponding true-pitch component. This value δ may be the same for all notes, or may be different for each note or groups of notes. Appropriate values of δ are stored in a memory **18** (FIG. **1**) accessed in unison with the frequency number memory **17** as each keyboard switch **12** is selected.

The value N designates the number of amplitude sample points computed for the note of lowest pitch (fundamental frequency) of the computor organ **10**. Satisfactory synthesis of pipe organ sounds is achieved using 32 such sample points ($N = 32$). Preferably the total number ($A + B$) of components calculated to synthesize the waveshape is equal to or less than $N/2$. This will satisfy the well known sampling rate requirements (related to the Nyquist criteria) of a sampled data system. In the embodiment of FIG. **1**, the computor organ **10** calculates eight Fourier components ($A = 8$, $B = 8$) for each of the two sets combined to obtain each waveshape sample point amplitude. Accordingly, the sample point amplitude $X_o(qR)$ is given by the relationship:

$$X_o(qR) = \sum_{n=1}^{A} F_A^{(n)} + \sum_{n=1}^{B} F_B^{(n)} = \sum_{n=1}^{A} C_n \sin\frac{2\pi}{N} nqR + \sum_{n=1}^{B} C_n' \sin\frac{2\pi}{N} nq(R+\delta) \qquad \text{(Eq. 3)}$$

which is a form of discrete Fourier representation of a sampled periodic complex waveshape.

In the embodiment of FIG. **1**, equation 3 is implemented by computing the amplitude value $x_o(qR)$ for each sample point during a fixed time interval t_x established by a clock **20** and a counter **21**. During each interval t_x individual Fourier components are calculated in successive time intervals designated t_{cp1} through t_{cp16} respectively. During the first eight intervals t_{cp1} through t_{cp8}, the eight true-pitch components (solid lines in FIG. **2**) are calculated in accordance with equation (1) above. The eight frequency-shifted components (broken lines in FIG. **2**) are calculated during the subsequent calculation intervals t_{cp9} through t_{cp16}, in accordance with equation (2) above. All of the calculated components are summed in the accumulator **13**, the contents of which, representing the amplitude value $x_o(qR)$, is gated to the digital-to-analog converter **16** at the end of the computation cycle t_x.

To this end, the clock **20** provides timing pulses at intervals t_{cp} via a line **22** to the counter **21**. The counter **21** preferably is of modulo **16**, and provides outputs t_{cp1} through t_{cp16} on the lines designated with corresponding numbers. The signals t_{cp1} through t_{cp8} all are provided via an OR-gate **23** onto a line **24** to control calculation of the true-pitch components. Similarly, the signals t_{cp9} through t_{cp16} all are supplied via an OR-gate **25** to a line **26** which controls calculation of the frequency-offset components. The t_{cp16} signal, slightly delayed in a delay unit **27**, provides the t_x signal on the line **15** indicating the end of the computation cycle.

To calculate each true-pitch harmonic component, the frequency number R associated with a selected note is supplied from the memory **17** via a line **28** and a gate **29** to a note interval adder **30**. The gate **29** is enabled by the t_x signal, so that the contents of the adder **30** is incremented each computation interval, and represents the value (qR) designating the waveshape sample point currently being evaluated.

At each interval t_{cp1} through t_{cp8}, the value (qR) is gated from the adder **30** via a line **32** and a gate **33** to a harmonic interval adder **34** which is cleared by the t_x signal at the beginning of each computation cycle. Accordingly, during the first eight calculation cycles, the contents of the adder **34** represents the value nqR (for $n = 1, 2, 3, \ldots 8$) designating which true-pitch harmonic component currently is being evaluated.

An address decoder **35** accesses from a sinusoid table **36** the value $\sin(2\pi/N)\, nqR$ corresponding to the argument nqR received via a line **35'** from the harmonic interval adder **34**. The sinusoid table **36** may comprise a read only memory storing values of $\sin(2\pi/N)\,\theta$ for $0 \leq \theta \leq N$ at intervals of D, where D is called the resolution constant of the memory.

The value $\sin(2\pi/N)\, nqR$, supplied via a line **37**, is multiplied by the coefficient C_n for the corresponding n^{th} harmonic by a multiplier **38**. The multiplication product represents the amplitude $F_A^{(n)}$ of the n^{th} true-pitch harmonic component, and is supplied via a line **39** to the accumulator **13**. The appropriate coefficient C_n is accessed from a harmonic coefficient memory **41**, described in more detail below, under direction of a memory address control unit **42** also receiving the computation interval signals t_{cp1} through t_{cp8} from the line **24**.

After the eighth true-pitch component has been calculated, the harmonic interval adder **34** is cleared. To accomplish this, the the t_{cp8} signal, slightly delayed by a delay unit **44**, is supplied via a line **45** to the "clear" input of the adder **34**.

To compute the frequency-offset components, the value δ associated with the selected note is accessed from the memory **18** and added to the frequency number R for that note by an adder circuit **46**. The sum $(R + \delta)$ is supplied to a second note interval adder **47** via a gate **48** actuated by the computation interval signal t_x on the line **15**. Accordingly, the note interval adder **47** during each computation interval will contain the sum $q(R + \delta)$. This value $q(R + \delta)$ in effect represents the sample point of a waveshape having a fundamental slightly higher in frequency, by an amount designated by δ, than the true-pitch fundamental of the same note.

At each interval t_{cp9} through t_{cp16} the value $q(R + \delta)$ is supplied via a line **49** and a gate **50** to the harmonic interval adder **34**. Accordingly, the contents of the adder **34** represents a quanitity $nq(R + \delta)$ for $n = 1, 2, 3, \ldots 8$ where n now indicates the harmonic order of the frequency-shifted Fourier components illustrated by the broken lines in FIG. **2**.

The memory address decoder **35** now accesses from the sinusoid table **36** the value $\sin(2\pi/N)\, nq(R + \delta)$ corresponding to the argument $nq(R + \delta)$ received from the harmonic interval adder **34** on the line **37**. This sin value, supplied via the line **37**, is multiplied by the appropriate harmonic coefficient C_n' obtained from the harmonic coefficient memory **41**. The memory address control **42** now receives the signals t_{cp9} through t_{cp16} on the line **26**, insuring that the appropriate values C_n' are supplied to the multiplier **38**.

The output of the multiplier **38** on the line **39** represents the value $F_B^{(n)}$ of the frequency-offset component currently being calculated. This value is supplied to the accumulator **13** where it is summed with the previously calculated true-pitch and frequency-shifted components. When all eight frequency-shifted components have been evaluated (i.e., after interval t_{cp16}) the contents of the accumulator **13** represents the value $x_o(qR)$ as given by equation (3) above. The t_x signal gates this value $x_o(qR)$ via the digital-to-analog converter **16** to the sound system **11**, and clears the accumulator **13** in readiness for computation of the next sample point amplitude. As the computations are carried out, the sound produced by the system **11** corresponds to the selected notes with a pleasing celeste effect.

The memory **41** advantageously comprises a read only memory containing harmonic coefficient values C_n and C_n' appropriate to produce a note of desired tonal quality. The values C_n may be the same as, or different from the values C_n' for like harmonics. In the former instance ($C_n = C_n'$) each frequency-offset harmonic component (broken lines in FIG. **2**) will have an amplitude equal to the corresponding true-pitch component. This in effect will synthesize a pipe organ sound wherein both celeste ranks are of like tonal quality. Alternatively, the values C_n may differ from the corresponding value C_n', producing a sound wherein the two celeste ranks have different voices.

The following Table I indicates typical values of C_n and C_n' for a flute voice and a soft string voice respectively wherein both celeste ranks are of like voice ($C_n = C_n'$) and for a celeste stop having ranks of different tonal quality ($C_n \neq C_n'$).

TABLE I

	Value Stored in Memory					
	Flute		Soft String		Mixed Voice	
Harmonic Coefficient	(Relative Amplitude)	Decibel Equivalent	(Relative Amplitude)	db Equivalent	(Relative Amplitude)	db Equivalent
C_1	127	0	127	0	127	0
C_2	0	−50	40	−10	40	−10
C_3	4	−30	16	−18	16	−18
C_4	0	−50	36	−11	36	−11
C_5	0	−50	6	−27	6	−27
C_6	0	−50	4	−30	4	−30
C_7	0	−50	5	−29	5	−29
C_8	0	−50	1	−44	1	−44
C_1'					127	0
C_2'	Same		Same		0	−50
C_3'	as		as		4	−30
C_4'	C_1—C_8		C_1—C_8		0	−50
C_5'	respectively		respectively		0	−50

TABLE I – Continued

Harmonic Coefficient	Value Stored in Memory: Flute (Relative Amplitude)	Flute Decibel Equivalent	Soft String (Relative Amplitude)	Soft String db Equivalent	Mixed Voice (Relative Amplitude)	Mixed Voice db Equivalent
C_6'					0	−50
C_7'					0	−50
C_8'					0	−50

The harmonic coefficient memory **41** and address control **42** together may be implemented using a single integrated circuit read only memory such as the Signetics type 8223. Such unit accepts a binary coded addressing signal. Correspondingly, the counter **21** may comprise a Signetics type 8281 16-state binary counter, the binary output of which may be supplied directly to the address control input of the type 8223 memory. A Signetics type 8250 binary-to-octal decoder may be used in conjunction with the type 8281 counter to provide the separate t_{cp1} through t_{cp16} signal lines shown in FIG. **1**. The type 8223 memory may be programmed to store the harmonic coefficients listed in Table I above, or other values of C_n and C_n' appropriate to produce other celeste voices.

The frequency number memory **17** and the δ memory **18** likewise may be implemented using the same or separate conventional integrated circuit read only memories such as the Signetics type 8223. The following table shows typical values for the frequency number R and δ values for the notes between C_3 and C_5.

TABLE II

Note	R	δ	Frequency Offset of Shifted Fundamental(Hertz)
C_3	0.0341	0.005	2.00
$C\#_3$	0.0361	0.005	2.10
D_3	0.0382	0.006	2.20
$D\#_3$	0.0405	0.006	2.25
E_3	0.0429	0.006	2.35
F_3	0.0455	0.006	2.45
$F\#_3$	0.0482	0.006	2.50
G_3	0.0510	0.007	2.60
$G\#_3$	0.0541	0.007	2.70
A_3	0.0573	0.007	2.75
$A\#_3$	0.0607	0.007	2.85
B_3	0.0643	0.008	2.95
C_4	0.0681	0.008	3.00
$C\#_4$	0.0722	0.008	3.10
D_4	0.0765	0.008	3.20
$D\#_4$	0.0810	0.009	3.30
E_4	0.0858	0.009	3.40
F_4	0.0909	0.009	3.45
$F\#_4$	0.0963	0.009	3.55
G_4	0.1021	0.009	3.60
$G\#_4$	0.1081	0.010	3.70
A_4	0.1146	0.010	3.75
$A\#_4$	0.1214	0.010	3.85
B_4	0.1286	0.010	3.90
C_5	0.1362	0.011	4.00

In the foregoing table, the frequency numbers are based on $N = 32$ sample points per period for the note C_7, and assume a monophonic instrument as shown in FIG. **1**. The listed δ values will provide the frequency-offset between the true-pitch and frequency-shifted fundamental components also specified in Table II. The δ values are a design choice selected to provide a pleasing celeste. In the example of Table II, different groups of notes have like frequency offset. As mentioned before, this is not necessary, and all notes could have the same offset, or each note could have a different frequency offset.

In the alternative embodiment of FIG. **3**, the computor organ **10'** calculates 15 true-pitch Fourier components $F_A^{(n)}$ (for $n = 1, 2, 3, \ldots, 15$) and a single component $F_B^{(1)}$ offset slightly higher in frequency than the true-pitch fundamental. The associated harmonic spectrum is shown in FIG. **4**. The true-pitch components are calculated during the time intervals t_{cp1} through t_{cp15} **24** and the offset component is evaluated at the calculation interval t_{cp16}.

To this end, the corresponding t_{cp1} through t_{cp15} outputs from the counter **21'** are supplied via an OR-gate **52** and a line **53** to the gate **33**. Thus the value nqR in the harmonic interval adder **34'** is incremented at each of these 15 consecutive calculation intervals. Accordingly, the true-pitch component values $F_A^{(n)}$ for $n = 1, 2, \ldots, 15$ successively are provided on the line **39'** for summation in the accumulator **13**. After the 15th true-pitch component $F_A^{(15)}$ has been calculated, the harmonic interval adder **34'** is cleared by the t_{15} signal, slightly delayed by a delay unit **54**.

The single frequency-offset component is calculated during the interval t_{cp16}. At the beginning of each computation cycle, the value δ associated with the selected note is accessed from the memory **18'** and supplied via a gate **55** to an interval adder **56**. The value δ is added to the previous contents of the interval adder **56**, so that the output on a line **57** represents the value $q\delta$. This is summed with the value qR from the note interval adder **30** by an adder **58** to obtain the value $q(R + \delta)$. At the calculation interval t_{cp16}, the value $q(R + \delta)$ is supplied from the adder **58** via a gate **59** to the harmonic interval adder **34'** upon occurrence of the t_{cp16} signal on a line **60**. Since the adder **34'** previously was cleared by the delayed t_{15} signal, the resultant contents of the adder **34'** will be simply $q(R + \delta)$.

The memory address decoder **35** then accesses from the sinusoid table **36** the value $\sin(2/N)\, q(R + \delta)$ corresponding to the argument $q(R + \delta)$ received from the adder **34'**. That sin value, provided via the line **37'**, is multiplied by the corresponding coefficient C_1' to provide the value $F_B^{(1)} = C_1' \sin(2\pi/N)\, q(R + \delta)$. This value $F_B^{(1)}$ is added in the accumulator **13** to the sum of the previously calculated 15 true-pitch components, to provide the sample point amplitude

$$x_o(qR) = \sum_{n=1}^{15} F_A^{(n)} + F_B^{(1)}.$$

This value of $x_o(qR)$ then is gated via the digital-to-analog converter **16** to the sound system **11**. Again there results a note having pleasant celeste characteristics.

FIG. **4** shows a typical harmonic spectrum of the celeste sound produced by the computor organ **10'** of FIG. **3**. The 15 true-pitch components are indicated by the solid lines, and the single frequency-offset component by the broken line. The relative amplitudes of the various components of course determine the tonal quality of the produced sound. By way of example, a rich string sound may be produced using the harmonic component values C_n and C_1' listed in the following Table III. These values are stored in the harmonic coefficient memory **41'** and appropriately accessed by the memory control **42'** which receives the calculation interval signals on the lines **53** and **60.**

TABLE III

Harmonic Coefficient	Value Stored in Memory Rich String Voice (Relative Amplitude)	(Decibel Equivalent)
C_1	80	−4
C_2	80	−4
C_3	101	−2
C_4	127	0
C_5	32	−12
C_6	36	−11
C_7	25	−14
C_8	18	−17
C_9	28	−13
C_{10}	16	−18
C_{11}	13	−20
C_{12}	7	−25
C_{13}	5	−28
C_{14}	3	−33
C_{15}	3	−33
C_1'	127	0

Celeste may be implemented for all notes of the organ, or only for some notes. Thus in the embodiment of FIG. **3,** celeste is produced for each note between C_3 and C_5. Celeste may be inhibited, as by appropriate logic **62,** when a note between C_1 and B_3 or between D_5 and C_7 is selected.

Illustrative celeste inhibit circuitry **62** is shown in FIG. **5.** The lines C_1 and B_3 and B_5 through C_7 from the corresponding keyboard (or pedal) switches **12** are supplied on an OR-gate **63.** When a note between C_3 and C_5 is played, a low output is present on the line **64** from the OR-gate **63,** indicating that celeste is to be implemented. This low signal is inverted by an inverter **65** to produce on a line **66** a high signal which enables a pair of AND-gates **67, 68.** The gates **67, 68** thus provide the t_{cp15} and t_{cp16} signals respectively to the delay unit **54** and the gate **59,** as shown in FIG. **3.** Normal celeste production occurs.

When a note between C_1 and B_3, or between B_5 and C_7 is played, the output of the OR-gate **63** on the line **64** is high. This functions as described below to inhibit celeste production. During the calculation interval t_{cp16} the offset harmonic component $F_B^{(1)}$ is not generated. Instead, a 16th ($n = 16$) true-pitch harmonic $F_A^{(16)}$ is produced.

When the output of the OR-gate **63** is high, the output of the inverter **65** is low, and the AND-gates **67, 68** are disabled. The t_{cp15} is not supplied to the delay unit **54,** hence the harmonic interval adder **34'** is not cleared at the end of the t_{cp15} interval. Further, the high signal on the line **64** enables an AND-gate **69,** which provides the t_{cp16} pulse via an OR-gate **70** to the gate **33.** As a result, during the time interval t_{cp16} the value (qR) is added to the contents of the harmonic interval adder **34',** so that the contents becomes $nqR = 16qR$. As a result, the sin value corresponding to that argument ($16qR$) is accessed from the sinusoid table **36** and to the harmonic amplitude multiplier **38.**

Similarly, the t_{cp16} signal is provided via the AND-gate **69** to the memory access control **42'.** This causes access from the harmonic coefficient memory **41'** of the value C_{16} (that is, the harmonic coefficient for the 16th true-pitch harmonic). As a result, the true-pitch harmonic $F_A^{(16)}$ is provided to the accumulator **13.** The resultant waveshape is obtained from 16 true-pitch harmonics and no frequency-offset components; this corresponds exactly to the production of a true-pitch note without celeste.

As shown in FIG. **6,** production of a celeste readily is implemented in a computor organ **75** using parallel processing. The organ **75,** like the instrument of FIG. **1,** calculates the same number of true-pitch and frequency-shifted components. The advantage of using parallel processing is that both sets of Fourier components are calculated concurrently, so that the system clock rate may be one-half that required for the computor organ **10** of FIG. **1.** As discussed in the above mentioned patent application entitled COMPUTOR ORGAN USING PARALLEL PROCESSING, this significant reduction in computation rate more readily permits the computor organ to be implemented using conventional integrated circuitry.

Referring to FIG. **6,** the computor organ **75** includes a first processing channel **76***a* in which the values $F_A^{(n)}$ for the true-pitch components are calculated, and a second, like parallel processing channel **76***b* wherein the values $F_B^{(n)}$ are calculated for the frequency-shifted components. System timing is established by a clock **77** having a rate one-half that of the clock **20** in FIG. **1.** The output pulses t_{cp}' from the clock **77** advance a binary counter **78** of modulo **8.** The output of the counter **78** on the lines **79***a*, **79***b*, **79***c* comprises a binary signal representing the respective counts t_{cp1}' through t_{cp8}'.

At the first interval t_{cp1}' the low order, true-pitch Fourier component $F_A^{(1)}$ is calculated in the channel **76***a* and concurrently the low order frequency-shifted component $F_B^{(1)}$ is calculated in the channel **76***b*. These components, present on the respective lines **80, 81** are summed by an adder **82** and supplied via a line **83** to an accumulator **13,** gate **14,** digital-to-analog converter **16** and sound system **11** like that of FIG. **1.** At consecutive intervals t_{cp2}' through t_{cp8}' successive pairs of true-pitch and frequency-shifted components $F_A^{(n)}$ and $F_B^{(n)}$ for values $n = 2,3, \ldots 8$ are computed, summed in the adder **82** and supplied to the accumulator **13.** In this manner, both sets of Fourier components are computed during eight time intervals t_{cp}', each of which intervals t_{cp}' is twice as long as the calculation interval t_{cp} of the FIG. **1** system.

The various components of the parallel processing organ **75** will be recognized by reference to FIG. **1.** However, separate harmonic interval adders **34***a*, **34***b* are used to accumulate the totals nqR and $nq(R + \delta)$ respectively. Both adders **34***a*, **34***b* are cleared by the t_x signal derived via a delay unit **84** from the t_{cp8}' signal. The values qR from the note interval adder **30***a* and $q(R + \delta)$ from the note interval adder **30***b* respectively are gated to the harmonic interval adders **34***a* and **34***b* via gates **33***a* and **33***b* enabled at each calculation interval t_{cp1}' through t_{cp8}'.

The timing signals t_{cp1}' through t_{cp8}' are derived from the binary counter **78** output using a binary-to-octal decoder **85.** The eight lines from the decoder **85,** containing the respective signals t_{cp1}' through t_{cp8}' all are connected to an OR-gate **86** the output of which, on a line **87,** enables the gates **33***a* and **33***b*.

Separate harmonic coefficient memories **41***a*, **41***b* and associated address control units **42***a*, **42***b* are used in the respective channels **76***a*, **76***b*. Each may be implemented using a Signetics type 8223 read only memory or the equivalent, the address control portion of which directly receives the binary coded count on the lines 79*a* – 79*c*. The memory 41*a* contains the true-pitch harmonic coefficients C_n and the memory 41*b* stores the coefficients C_n' for the frequency-shifted components. These values may correspond to those set forth above in Table I.

Although the embodiments shown in the drawings each calculate two sets of Fourier components, the invention is not so limited. Thus three or more sets of components could be evaluated and summed to obtain each sample point amplitude. In such case, all three sets may be slightly offset in frequency from each other. Further, even in the two set embodiments, it is not required that the components of either set correspond in frequency to the true pitch of the selected note. Thus, e.g., one set may be tuned slightly below true pitch, the other slightly above. Advantageously, but not necessarily, the musical instruments disclosed herein are implemented digitally.

TABLE A

Component (FIG. 1)	Conventional Integrated Circuit* (or other reference)	Remarks
Frequency number memory 17	(a)SIG 8223 field-programmable read only memory (ROM) [p. 37] (b)TI SN5488A, SN7488A 256-bit ROM [p. 9–235]	Typical values of R and δ are listed in Table II of specification
δ memory 18		
Note interval adders 30,47	(a)SIG. 8260 arithmetic logic element [p. 37] (b)SIG. 8268 gated full adder [p. 97] (c)TI SN5483, SN7483 4-bit binary full adders [p. 9–271] (may be connected as shown in Flores[1] Section 11.1 to accumulate sum)	
Harmonic interval adder 34	Same as note interval adder 30	
R+δ Adder 46	SIG. 8268 gated full adder	
Gates 14,29,33, 48,50	TI SN5408, SN5409 quadruple AND gates [p. 6–17]	
Sinusoid table 36 and memory address decoder 35	(a)TI TMS4405 sinusoid table and addressing circuitry (b)TI TMS4400 ROM containing 512 words of eight-bits [p. 14–188] programmed to store sin values	Roundoff, if required, may be implemented per Ledley[2] section 4–6.
Harmonic coefficient memory 41 and memory address control 42	(a)SIG 8223 read only memory which includes address control circuitry (b)TI SN54166 series shift registers [p.9–134]	See Table I for examplary contents
Harmonic Amplitude Multiplier 38	(a)May be implemented as shown in application sheet, SIG. catalog, p.28 using SIG 8202 buffer registers and 8260 arithmetic element (b)Also can be implemented using SIG 8243 scaler [p.65]	
Accumulator 13	(a)SIG 8268 or TI SN5483, SN7483 full adders connected as shown in Flores[1], section 11.1 "Accumulators".	

TABLE A–Continued

Component (FIG. 1)	Conventional Integrated Circuit* (or other reference)	Remarks
Counter 21	(a)SIG 8281 sixteen-state binary counter [p. 123], and a SIG 8250 binary-to-octal decoder	
Clock 20	Any oscillator	

*TI=Texas Instrument Co.
[Page references are to the TI "Integrated Circuits Catalog for Design Engineers", First Edition, January, 1972]
SIG=Signetics, Sunnyvale, California
[Page references are to the SIG "Digital 8000 Series TTL/MSI" catalog, copyright 1971]
Flores, Ivan "Computer Logic" Prentice-Hall, 1960
Ledley, Robert "Digital Computer and Control Engineering" McGraw-Hill, 1960

Intending to claim all novel, useful and unobvious features shown or described, the applicant makes the following claims:

1. Apparatus for production of celeste in a computor organ comprising:

first means, operative during repetitive computation intervals, for separately calculating a first set of Fourier components associated with the musical waveshape of a first note of one pitch; and second means, also operative during said repetitive computation intervals, for separately calculating a second set of Fourier components associated with the musical waveshape of a second note having a pitch slightly offset in frequency with respect to said first note,

means for combining the calculated components of said first and said second sets within each computation interval to establish a sample point amplitude of a resultant musical waveshape the shape of which varies in time as a result of the frequency difference between said first and second notes,

means operative at the end of each computation interval for incrementing the effective sample point for which said resultant waveshape amplitude is established, and

means for converting said resultant waveshape amplitudes to sounds in real time, the sounds so produced exhibiting a celeste effect.

2. Celeste production apparatus according to claim 1 wherein said calculating and combining is performed digitally, wherein said means for converting includes a digital-to-analog converter and a sound system for reproducing the output from said converter, and wherein each component amplitude is established by a set of coefficients stored digitally, the relative amplitudes of said components establishing the tonal quality of the produced sounds.

3. Celeste production apparatus according to claim 1 wherein components of said first set are calculated at effective waveshape sample points separated by qR wherein R is a frequency number establishing the fundamental period of said first note and q is an integer incremented at the end of each computation interval and wherein components of said second set are calculated at effective waveshape sample points separated by $q(R+\delta)$ wherein δ is a value designating the amount of frequency offset of said second note.

4. Celeste production apparatus according to claim 1 comprising:

a clock for establishing said repetitive computation intervals,

a frequency number memory storing values R which establish the effective waveshape sample point separation for corresponding notes,

a δ memory storing harmonic offset values δ for selectable notes,

a keyboard for selecting notes to be produced by said apparatus, actuation of a key on said keyboard causing memory readout of the R and δ values for the selected note,

note interval adders for establishing values of (qR) and $q(R+\delta)$ for selected notes during successive computation intervals, where q is an integer incremented by said means for incrementing, and wherein said first means comprises

circuitry, cooperating with said note interval adders, for evaluating said first set $F_A^{(n)}$ of Fourier components in accordance with the relationship

$$F_A^{(n)} = C_n \sin (2\pi/N)\, nqR$$

and wherein said second means comprises circuitry, also cooperating with said note interval adders, for evaluating said second set $F_B^{(n)}$ of Fourier components in accordance with the relationship

$$F_B^{(n)} = C_n' \sin (2\pi/N)\, nq\,(R+\delta)$$

wherein A and B represent the number of Fourier components includes in said respective first and second sets, components in said second set being shifted in frequency with respect to said first set by an amount established by said values δ, wherein C_n and C_n' are coefficients indicating the relative amplitude of the corresponding n^{th} component in the respective first and second set, and wherein N is a system constant.

5. As a musical instrument exhibiting a:

first means for computing at regular time intervals t_x the amplitudes $x_o\,(qR)$ of a waveshape, where q is an integer incremented each time interval t_x, in accordance with the relationship

$$X_o(qR) = \sum_{n=1}^{A} C_n \sin \frac{2\pi}{N} nqR + \sum_{n=1}^{B} C_n' \sin \frac{2\pi}{N} nq(R+\delta)$$

wherein A and B represent the number of Fourier components included in respective first and second sets defining said waveshape, components in said second set being shifted in frequency with respect to components of said first set by an amount established by δ, wherein C_n and C_n' are coefficients establishing the relative amplitudes of the corresponding n^{th} components in the respective first and second sets, wherein R is a number specifying the period of said waveshape, and wherein N is a system constant, said first means comprising;

a coefficient memory storing said harmonic coefficients C_n and C_n',

a sinusoid table comprising a memory storing values of $\sin (2\pi/N)\ \theta$ for $0 \leq \theta \leq N$ at intervals of D where D is a resolution constant,

a frequency number memory containing values of R associated with selectable musical notes, a δ memory containing values of δ associated with said notes, and note selection circuitry for accessing from said frequency number and δ memories the values R and δ for each selected note,

harmonic component evaluation circuitry utilizing said coefficient memory and said sinusoid table to calculate

$F_A^{(n)} = C_n \sin (2\pi/N)\ nqR\ (n = 1,2, \ldots A)$

for each of the A Fourier components in said first set in accordance with the selected value R, and to calculate

$F_B^{(n)} = C_n' \sin (2\pi/N)\ nq(R + \delta)\ (n = 1,2, \ldots B)$

for each of the B Fourier components in said second set in accordance with the selected values R and δ, and

an accumulator for algebraically summing the calculated values $F_A^{(n)}$ and $F_B^{(n)}$ to obtain each waveshape amplitude $X_o(qR)$, and

second means responsive to said first means for providing celeste tones from said computed amplitudes.

6. A musical instrument according to claim **5** wherein said calculations are performed digitally, wherein said second means includes a digital-to-analog converter and a sound system for converting said obtained waveshape amplitudes to musical sounds exhibiting a celeste effect, successive cycles of said obtained waveshape being of different shape.

7. A musical instrument according to claim **5** wherein said first means includes:

a clock and counter defining calculation subintervals within said regular interval t_x, components of said first and second sets being calculated during said subintervals.

8. A musical instrument according to claim **5** together with means for preventing calculation of components in said second set when notes having certain values of R are selected.

9. A musical instrument according to claim **5** wherein $A = B$.

10. A musical instrument according to claim **9** wherein $C_n = C_n'$ for corresponding values of n.

11. A musical instrument according to claim **9** wherein $C_n \quad C_n'$ for corresponding values of n.

12. A musical instrument according to claim **5** wherein $B = 1$, the frequency of the single component in said second set being slightly higher than the fundamental ($n = 1$) component of said first set.

13. A musical instrument according to claim **5** wherein N represents the number of waveshape sample points for the tone of lowest fundamental frequency produced by said instrument, and wherein $A+B \quad N/2$.

14. A musical instrument according to claim **5** wherein the components of said first set are harmonically related in frequency to the true pitch of a selected note and wherein each component of said second set is offset slightly higher in frequency from the corresponding component of said first set.

15. A musical instrument according to claim **5** wherein the values δ are selected so that the frequency offset of the $(n = 1)^{th}$ component of said second set is in the range of from about 2 Hz to about 4 Hz.

16. A musical instrument according to claim **5** wherein said first means includes parallel processing channels for concurrently calculating components of said first and second sets.

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