United States Patent [19]

Deutsch

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[45] **May 7, 1974**

[54] **IMPLEMENTATION OF COMBINED FOOTAGE STOPS IN A COMPUTOR ORGAN**

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

[22] Filed: **Jan. 31, 1973**

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[52] **U.S. Cl.** **84/1.01**, 84/1.22, 84/1.23

[51] **Int. Cl.** **G10h 1/06**, G10h 5/02

[58] **Field of Search** 84/1.01, 1.03, 1.22, 1.23

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Attorney, Agent, or Firm—Howard A. Silber; Flam & Flam

[57] **ABSTRACT**

Combined footage stops are implemented in a computor organ of the type wherein musical notes are produced by computing successive sample point amplitudes of a musical waveshape and converting the amplitudes to sound as the computations are performed in real time. Each waveshape amplitude is obtained by evaluating those Fourier components comprising an incomplete set of harmonics for a first footage voice, and the fundamental and several low order odd harmonics of a voice of lower footage. In a preferred embodiment, an incomplete 8-foot harmonic series is employed, together with the first four odd harmonics of a 16-foot series. The 8-foot harmonics correspond in frequency to even harmonics of the 16-foot series. The missing 8-foot components are "reinstated" by the listener's ear. As a result, the combined voice is perceived just as though separate, complete spectra had been used to generate the waveshape. To implement shorter footage stops, certain of the 8-foot harmonics are excluded from the waveshape computation. For combined voices including shorter footage stops, the sum of the harmonic coefficients associated with the concurrently selected stops are used in the component calculations.

12 Claims, 10 Drawing Figures

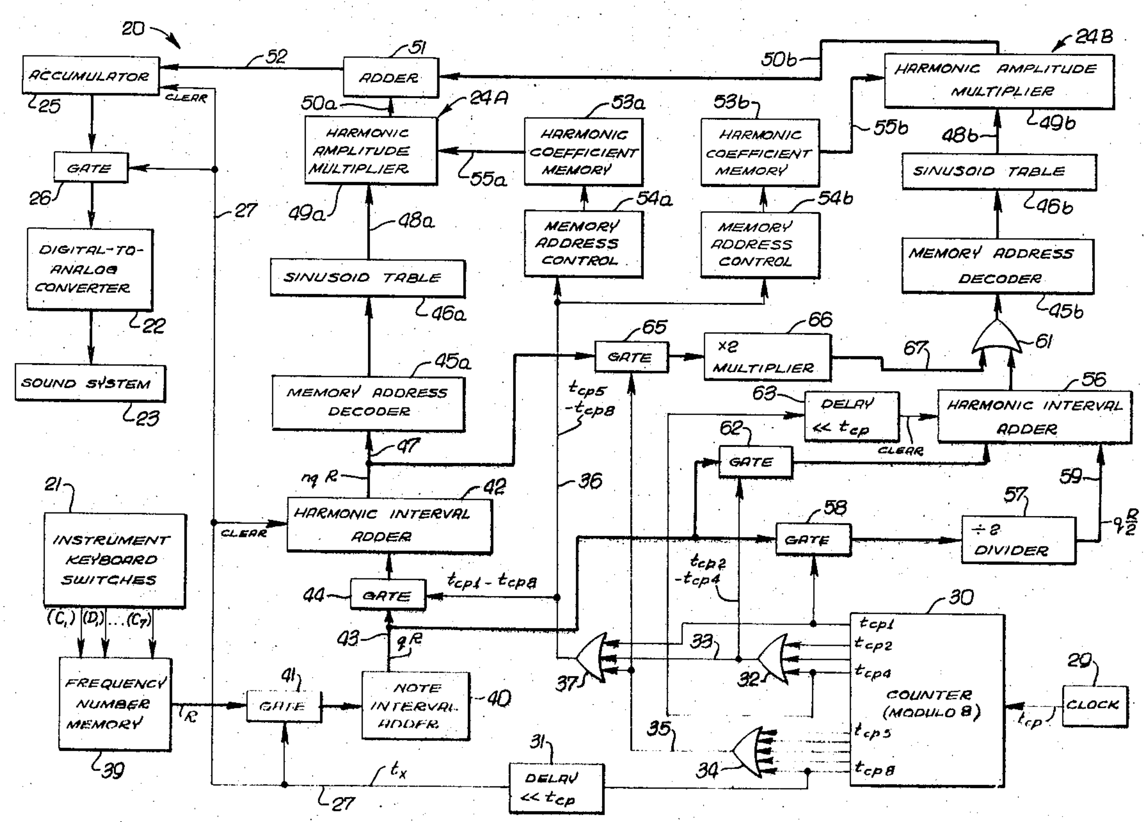


FIG. 1.

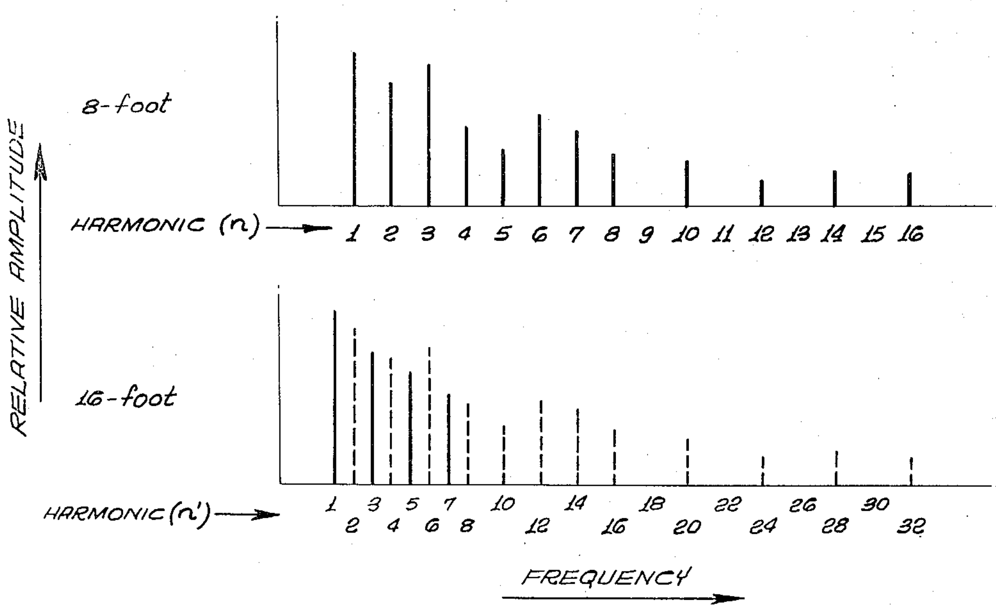
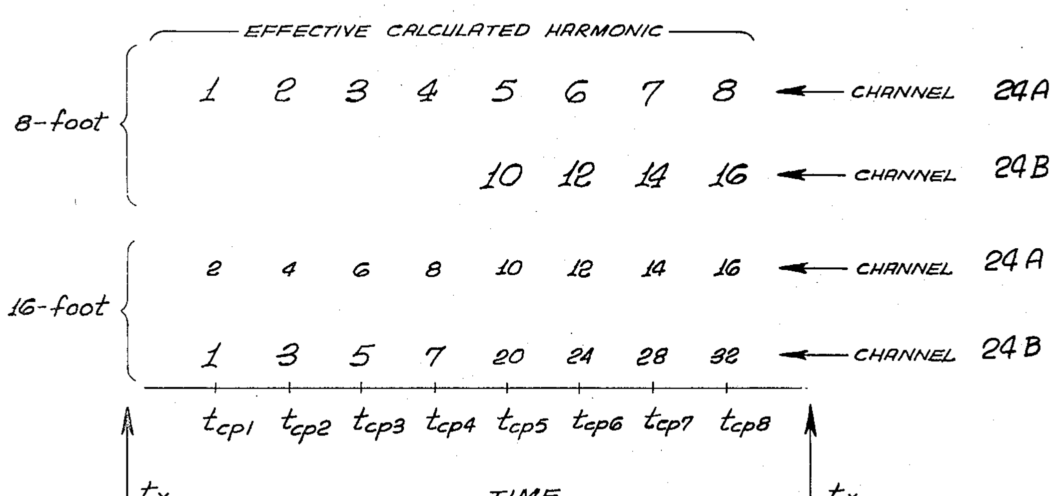

8-foot
16-foot
RELATIVE AMPLITUDE
HARMONIC (n)
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
HARMONIC (n')
1 3 5 7 10 14 18 22 26 30
2 4 6 8 12 16 20 24 28 32
FREQUENCY

FIG. 2.


EFFECTIVE CALCULATED HARMONIC
8-foot
1 2 3 4 5 6 7 8 CHANNEL 24A
10 12 14 16 CHANNEL 24B
16-foot
2 4 6 8 10 12 14 16 CHANNEL 24A
1 3 5 7 20 24 28 32 CHANNEL 24B
tcp1 tcp2 tcp3 tcp4 tcp5 tcp6 tcp7 tcp8
tx
TIME
tx

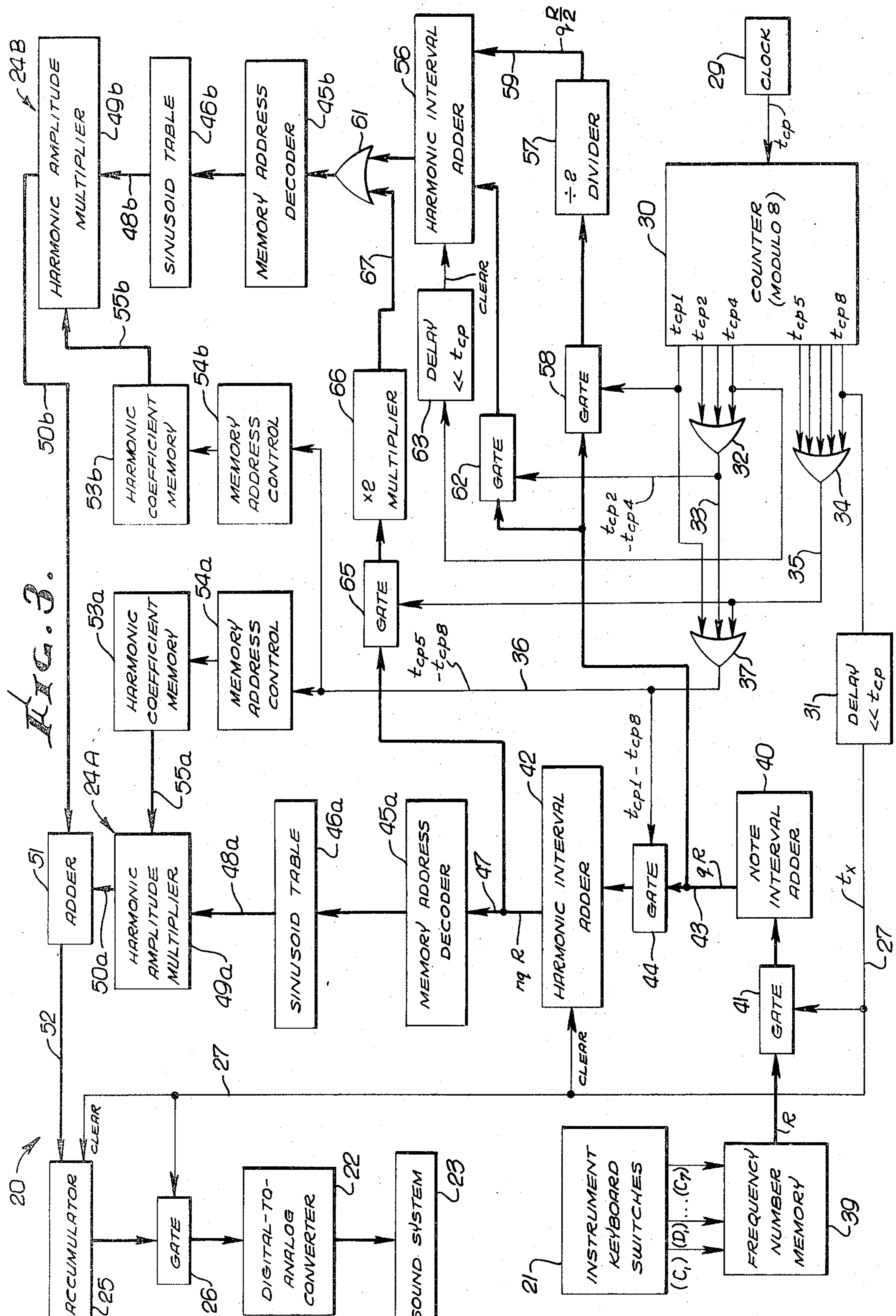

24B
HARMONIC AMPLITUDE MULTIPLIER
49b
SINUSOID TABLE
46b
48b
MEMORY ADDRESS DECODER
45b
61
HARMONIC INTERVAL ADDER
56
59
qR/2
÷2 DIVIDER
57
CLOCK
29
t_{cp}
COUNTER (MODULO 8)
30
t_{cp1}
t_{cp2}
t_{cp4}
t_{cp5}
t_{cp8}
67
CLEAR
DELAY << t_{cp}
63
55b
50b
HARMONIC COEFFICIENT MEMORY
53b
MEMORY ADDRESS CONTROL
54b
x2 MULTIPLIER
66
GATE
62
GATE
58
32
33
34
35
t_{cp2} - t_{cp4}
GATE
65
t_{cp5} - t_{cp8}
36
37
HARMONIC COEFFICIENT MEMORY
53a
MEMORY ADDRESS CONTROL
54a
DELAY << t_{cp}
31
t_{cp1} - t_{cp8}
42
40
ADDER
51
24A
HARMONIC AMPLITUDE MULTIPLIER
55a
50a
49a
48a
SINUSOID TABLE
46a
MEMORY ADDRESS DECODER
45a
47
HARMONIC INTERVAL ADDER
mqR
GATE
44
43
qR
NOTE INTERVAL ADDER
t_x
27
GATE
41
52
27
CLEAR
CLEAR
20
ACCUMULATOR
25
GATE
26
DIGITAL-TO-ANALOG CONVERTER
22
SOUND SYSTEM
23
INSTRUMENT KEYBOARD SWITCHES
21
(C_1) (D_1) ... (C_7)
R
FREQUENCY NUMBER MEMORY
39

FIG. 3.

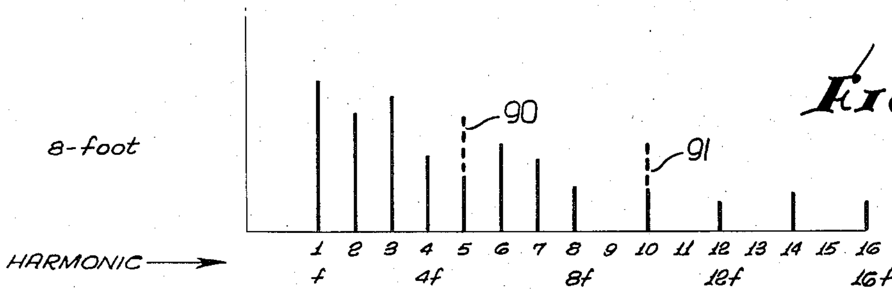


FIG. 4a.

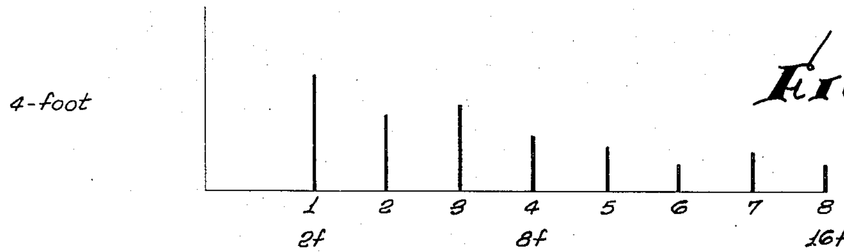


FIG. 4b.

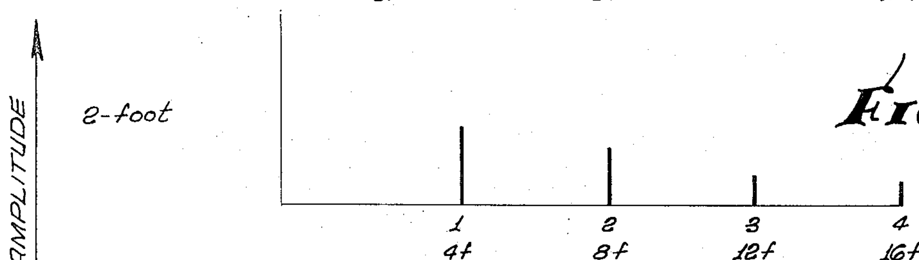


FIG. 4c.

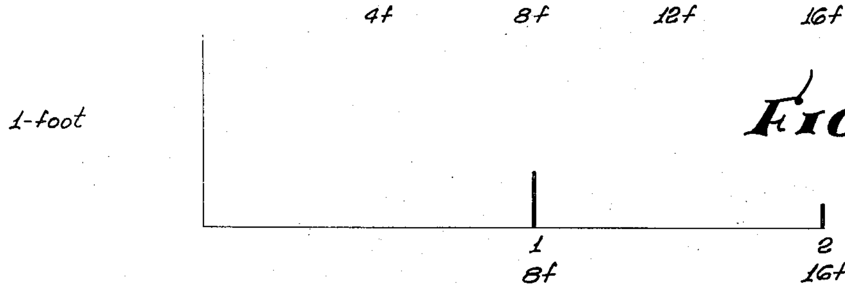


FIG. 4d.

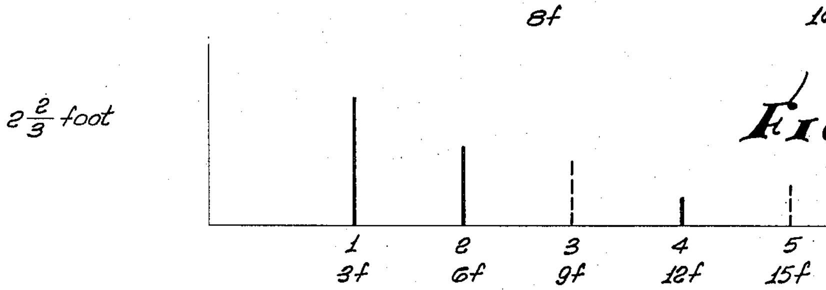


FIG. 4e.

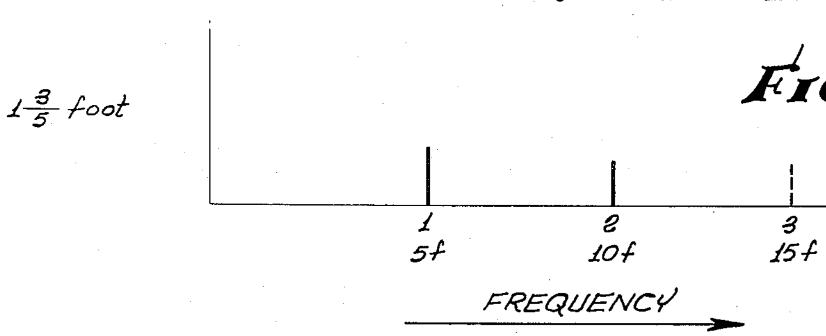
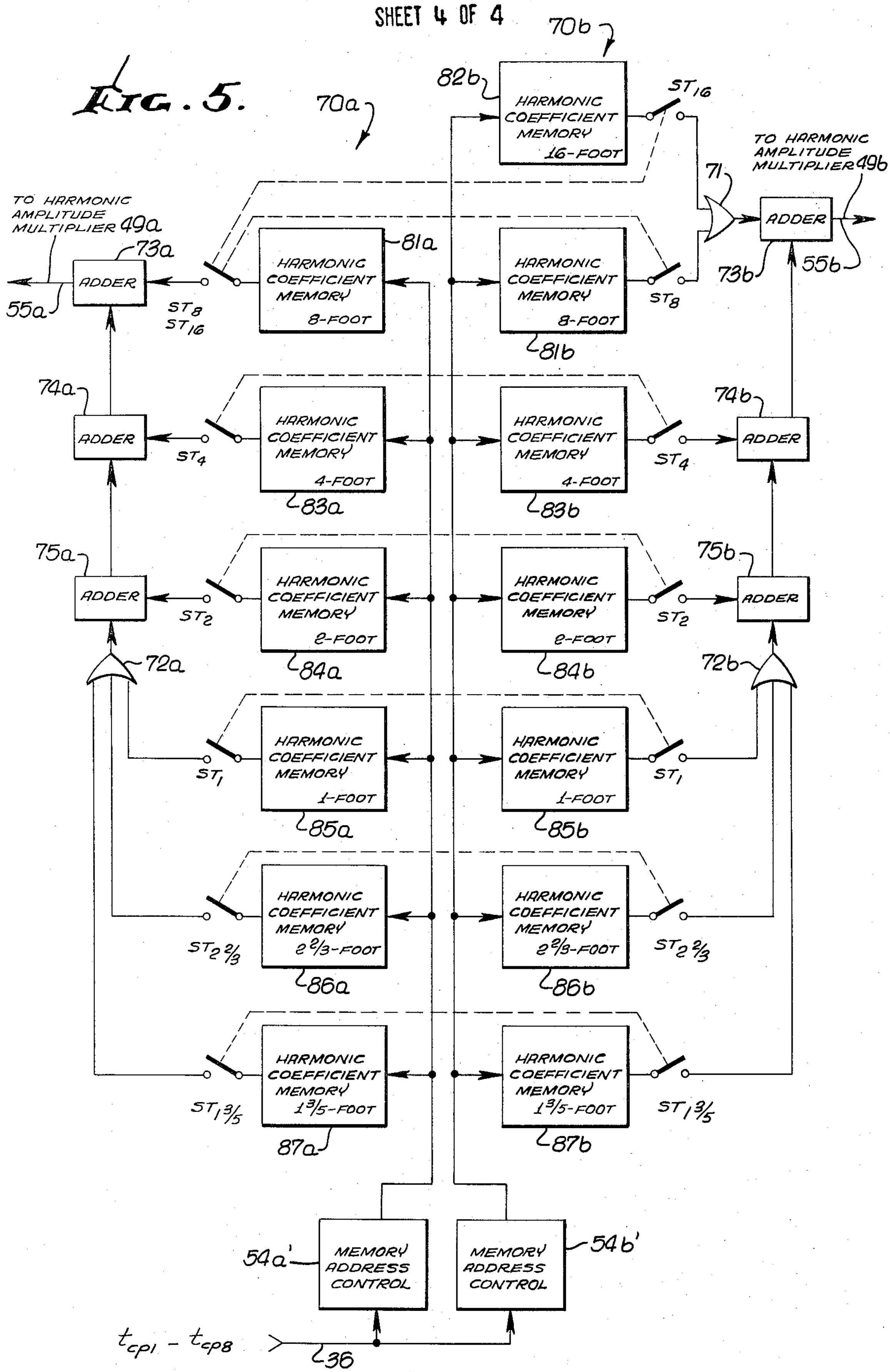


FIG. 4f.

FIG. 5.


70a
70b
82b
HARMONIC COEFFICIENT MEMORY 16-FOOT
ST_{16}
71
TO HARMONIC AMPLITUDE MULTIPLIER 49b
ADDER
73b
55b
TO HARMONIC AMPLITUDE MULTIPLIER 49a
73a
ADDER
55a
ST_8
ST_{16}
HARMONIC COEFFICIENT MEMORY 8-FOOT
81a
HARMONIC COEFFICIENT MEMORY 8-FOOT
81b
ST_8
74a
ADDER
ST_4
HARMONIC COEFFICIENT MEMORY 4-FOOT
83a
HARMONIC COEFFICIENT MEMORY 4-FOOT
83b
ST_4
74b
ADDER
75a
ADDER
ST_2
HARMONIC COEFFICIENT MEMORY 2-FOOT
84a
HARMONIC COEFFICIENT MEMORY 2-FOOT
84b
ST_2
75b
ADDER
72a
72b
ST_1
HARMONIC COEFFICIENT MEMORY 1-FOOT
85a
HARMONIC COEFFICIENT MEMORY 1-FOOT
85b
ST_1
$ST_{2\,2/3}$
HARMONIC COEFFICIENT MEMORY 2 2/3-FOOT
86a
HARMONIC COEFFICIENT MEMORY 2 2/3-FOOT
86b
$ST_{2\,2/3}$
$ST_{1\,3/5}$
HARMONIC COEFFICIENT MEMORY 1 3/5-FOOT
87a
HARMONIC COEFFICIENT MEMORY 1 3/5-FOOT
87b
$ST_{1\,3/5}$
54a'
MEMORY ADDRESS CONTROL
MEMORY ADDRESS CONTROL
54b'
$t_{cp1} - t_{cp8}$
36

IMPLEMENTATION OF COMBINED FOOTAGE STOPS IN A COMPUTOR ORGAN

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to implementation of combined footage stops in a computor organ.

2. Specific Related Applications

The present invention is related to the inventor's co-pending U.S. patent applications Ser. No. 225,883 filed Feb. 14, 1972 entitled COMPUTOR ORGAN, and Ser. No. 298,365 filed Oct. 17, 1972 entitled COMPUTOR ORGAN USING PARALLEL PROCESSING.

3. Description of the Prior Art

In a pipe organ, when an 8-foot stop is actuated, notes are produced at the same pitch as the selected key. Thus if the manual key C_4 is depressed, the note C_4 (the key of C in octave 4) will be sounded. Should a 16-foot stop be selected, the organ will produce notes one octave lower than the corresponding key. Thus if the manual key C_4 is depressed, C_3 will be sounded. Notes of higher octaves are produced when foundation stops of other footage are selected. For example, a 4-foot stop and a 2-foot stop respectively result in production of notes two and four octaves higher than the key being played.

Occasionally a musician will simultaneously select two or more stops of different footage. If a 16-foot and an 8-foot stop both are actuated, the organ simultaneously will produce sounds at both the notation frequency and one octave lower. An additional footage stop may be drawn to enhance certain harmonics of the basic footage. For example, a 1 3/5-foot stop may be used to enhance the fifth and 10th harmonics of a simultaneously selected 8-foot stop.

An objective of the present invention is the implementation of combined footage in a computor organ of the type described in the above-mentioned patent applications. In such an instrument, musical sounds are generated by computing in real time the amplitudes at successive sample points of a musical waveshape and converting these amplitudes to sounds as the computations are carried out. Each amplitude is obtained by individually calculating the Fourier components contributing to that waveshape. A set of stored harmonic components specifies the relative amplitude of each such component, thus establishing the wave shape and hence the tonal quality of the produced sound.

Combined footage could be implemented in such a computor organ by separately calculating, during each amplitude computation period, the harmonics associated with all selected stops. Should 8-foot and 16-foot stops simultaneously be selected, this seemingly straightforward approach would require calculation of twice the number of Fourier components normally calculated in the same time period, if only a single stop were selected. Since each sample point amplitude must be computed within a fixed time interval, such approach would require evaluation of individual components at twice the calculation speed required for a single footage stop. This is unsatisfactory, since the system speed requirements may exceed the capabilities of presently available integrated circuits. Alternatively, additional parallel computation channels could be used to evaluate the combined footage components. However, such added circuitry could as much as double the cost of the instrument.

The present invention provides a novel implementation for combined footage which permits generation, e.g., of simultaneously selected 8-foot and 16-foot stops without requiring either an increase in component calculation speed or the provision of additional computation channels.

SUMMARY OF THE INVENTION

The foregoing objective is achieved by taking advantage of two factors. One is that the harmonics of an 8-foot series correspond to the even harmonics of a 16-foot stop. These corresponding harmonics need not be separately calculated when synthesizing a combined 8-foot and 16-foot tone. Secondly, certain harmonics can be eliminated without any appreciable loss in tonal quality of the synthesized organ sound. The present invention utilizes both factors. During each amplitude computation interval, the computor organ calculates the Fourier components of an incomplete 8-foot harmonic spectrum, and also calculates certain low order, odd harmonics of the 16-foot spectrum. When combined to obtain the waveshape amplitude, the resultant sound has the tonal quality of combined 8- and 16-foot stops.

FIG. 1 illustrates typical 8-foot and 16-foot spectra generated by a computor organ using the inventive combined footage implementation. The 8-foot spectra includes the harmonics 1 through 8, 10, 12, 14 and 16. The 9th, 11th, 13th and 15th harmonics are not produced. These missing harmonics do not detract appreciably from the tonal quality of the generated organ sound. One reason is that for typical organ pipes, relatively little energy is contained in the higher harmonics. The first eight harmonics all are present; usually these are the strongest and dominate the tone coloring.

A more subtle reason relates to human sound perception. A psychoacoustic effect occurs whereby the ear tends to "reinsert" the missing harmonics. Since the human auditory system is non-linear, an apparent interference or "beat" effect occurs between the harmonics which are present. For example, the 10th harmonic appears to beat with the fundamental to provide the apparent tone coloring of the missing 9th and 11th harmonics. Similarly, the presence of the 12th, 14th and 16th harmonics causes the ear to reconstruct the missing 11th, 13th and 15th harmonic components.

As noted earlier, the 8-foot harmonic components correspond to the even components of a 16-foot series. In accordance with the present invention, the corresponding 16-foot even harmonic components (indicated by broken lines in FIG. 1) are not separately evaluated. However, the first four low order odd harmonics of the 16-foot series are calculated, as indicated by the solid lines in FIG. 1. These 16-foot components are evaluated during the time intervals normally allocated to calculation of those components which are missing from the 8-foot spectrum. The result is an effective 16-foot spectrum including the first eight harmonics, every other harmonic up to the 16th, and every fourth harmonic from the 20th through the 32nd. The above described psychoacoustic effect causes the apparent reinsertion of the missing 16-foot harmonics in the perceived tone. With the present invention, excellent combined footage stops can be simulated even though only the sixteen separate components shown in solid lines in FIG. 1 are evaluated.

The timing diagram of FIG. 2 illustrates how these 16 components may be evaluated within each fixed computation interval t_x by a two-channel computor organ like that of FIG. 3. One computation channel **24A** is allocated to calculation of the first eight 8-foot harmonics, as designated by the large numerals in the top row of FIG. 2. The remaining high order 8-foot harmonic components, and the four low order, odd harmonics of the 16-foot series are evaluated in a parallel computation channel **24B**. The small numerals in FIG. 2 designate the 16-foot components which correspond to the generated 8-foot components; these 16-foot components, indicated by the broken lines of FIG. 1, are not separately calculated by the computor organ.

The inventive combined footage implementation also permits generation of other foundation stops. As illustrated by FIG. 4, the 4-foot, 2-foot and 1-foot foundation stops will have no missing components, even though the 8-foot series is incomplete. The 2 ⅔-foot and 1 3/5-foot stops respectively will have two and one missing components. However, since these stops normally are selected to enhance specific harmonics in an 8-foot series, the missing components will have little practical effect on the perceived organ tones.

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 shows the harmonic spectra of combined 8-foot and 16-foot stops as synthesized by a computor organ using the inventive combined footage implementation.

FIG. 2 is a timing diagram indicating the calculation intervals during which the spectral components of FIG. 1 are evaluated within each computor organ computation interval.

FIG. 3 is an electrical block diagram of a computor organ employing the combined footage implementation of the present invention.

FIGS. 4A through 4F show spectra of other footage stops implemented with the present invention.

FIG. 5 is an electrical block diagram showing a modification to the system of FIG. 3 for implementing the other footages of FIG. 4.

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.

Combined footage is implemented by the computor organ **20** of FIG. 3. When a note is selected at the keyboard switches **21** a waveshape is computed digitally and converted to sound by a digital-to-analog converter **22** and a sound system **23**. The waveshape amplitude is computed for successive sample points at regular time intervals t_x. Within each such interval t_x the first eight harmonics of the 8-foot spectra (FIG. 1) are separately evaluated in a first processing channel **24A**. Within each same interval t_x the first four odd harmonics of the 16-foot spectra (FIG. 1) and the 10th, 12th, 14th and 16th 8-foot harmonic components are evaluated in a second parallel processing channel **24B**.

All of the components are summed algebraically in an accumulator **25** which, at the end of each computation interval t_x, contains the amplitude at the present sample point. This amplitude is provided to the digital-to-analog converter **22** via a gate **26** enabled by a t_x signal on a line **27**. Computation of the amplitude for the next sample point immediately is initiated, so that the analog voltage supplied from the converter **17** comprises a musical waveshape generated in real time and having a spectral content characteristic of combined footage.

In the present invention, the amplitude contribution $F_8^{(n)}$ of each 8-foot component is evaluated in accordance with the following relationship:

$$F_8^{(n)} = C_n \sin (\pi/W)\, nqR \text{ for } q=1,2,3 \ldots \quad \text{(Eq.1)}$$

where R is a frequency number associated with the note selected at the keyboard switches **12**. The number n designates the harmonic component being evaluated. Thus for the implementation of FIG. 1, n=1,2,3,4,5,6,7,8,10,12,14,16 corresponding respectively to the harmonics shown in solid lines in FIG. 1.

The harmonic coefficient C_n in equation 1 specifies the relative amplitude of the respective n^{th} 8-foot harmonic component. The value W designates the total number of harmonics included in the amplitude computation; this number is a design choice. The value W=16 is quite satisfactory for synthesizing pipe organ sounds, and this value is used in the embodiment of FIGS. 1 – 3. The harmonic amplitudes $F_8^{(n)}$ for n=1,2, . . . 8 are evaluated in the channel **24A**; the values $F_8^{(n)}$ for n=10,12,14,16 are evaluated in the channel **24B**.

The amplitude contribution $f_{16}^{(n')}$ of each 16-foot odd harmonic component is evaluated in accordance with the following equation:

$$F_{16}^{(n')} = C_n' \sin(\pi/W)\, n'q(R/2) \text{ for } q=1,2,3 \ldots \quad \text{(Eq.2)}$$

wherein n'=1,3,5,7 and wherein C_n' is a harmonic coefficient specifying the relative amplitude of the respective n'th 16-foot harmonic component. These values $F_{16}^{(n')}$ also are evaluated in the processing channel **24B**.

The waveshape amplitude $x_o(qR)$ for each sample point qR is given by the relationship:

$$x_o(qR) = \sum_{n=1}^{8} F_8^{(n)} + \sum_{\substack{n=10,12,\\14,16,}} F_8^{(n)} + \sum_{n'=1}^{4} F_{16}^{(n')} \quad \text{(Eq. 3)}$$

It is this value $x_o(qR)$ which is obtained in the accumulator **25** during each computation interval t_x and which is gated via the converter **22** to the sound system **23** at the end of each such interval.

As indicated in FIG. **2**, each computation interval t_x is divided into eight subintervals t_{cp1} through t_{cp8} during which the harmonic components are calculated. Such system timing is established by a clock **29** which provides pulses at intervals t_{cp} to a counter **30** of modulo $W/2 = 8$. The counter **30** produces consecutive output signals t_{cp1} through t_{cp8} on the correspondingly designated lines. The t_{cp8} signals, slightly delayed in a delay unit **31**, serve as the computation interval pulses t_x on the line **27**. For various gating functions described below, the timing signals t_{cp2} through t_{cp4} are combined by an OR-gate **32** and provided to a line **33**. The pulses t_{cp5} through t_{cp8} all are supplied via an OR-gate **34** to a line **35**. All eight timing signals t_{cp1} through t_{cp8} appear on a line **36** supplied by an OR-gate **37**.

In the computor organ **20**, a set of frequency numbers R corresponding to the notes of the instrument is stored in a frequency number memory **39**. A note interval adder **40** contains the value qR identifying the sample point at which the waveshape amplitude presently is being evaluated. This value qR is incremented at the beginning of each computation interval by adding the selected frequency number R to the previous contents of the adder **40**. To this end, the value R is gated to the adder **40** via a gate **41** enabled by the t_x signal on the line **27**. Preferably the adder **40** is of modulo $W/2$.

To calculate the first eight 8-foot harmonic components, the values nqR for $n=1,2,3,\ldots,8$ are obtained in a harmonic interval adder **42** which is cleared by the t_x signal at the end of each amplitude computation cycle. Upon occurrence of the first clock pulse t_{cp1} of each computation cycle, the present value qR contained in the note interval adder **40** is entered into the harmonic interval adder **42** via a line **43** and a gate **44** enabled by the pulses on the line **36**. At each subsequent clock pulse t_{cp2} through t_{cp8}, the value qR is added to the previous contents of the adder **42**. As a result, the harmonic interval adder **42** will contain the value nqR (for $n=1,2,\ldots 8$) for the n^{th} low order 8-foot harmonic component currently being evaluated in the channel **24A**. Preferably the harmonic interval adder **42** also is of modulo $W/2$.

An address decoder **45***a* accesses from a sinusoid table **46***a* the value $\sin(\pi/W)\,nqR$ corresponding to the argument nqR received via a line **47** from the harmonic interval adder **42**. The sinusoid table **46***a* may comprise a read-only memory storing values of $\sin(\pi/W)\,\theta$ for $0 \leq \theta \leq 2W$ at intervals of D, where D is called the resolution constant of the memory.

The value $\sin(\pi/W)\,nqR$, supplied via a line **48***a*, is multiplied by the coefficient C_n for the corresponding n^{th} harmonic by a multiplier **49***a*. The multiplication product represents the amplitude $F_A^{(n)}$ of the n^{th} low order 8-foot harmonic component, and is supplied via a line **50***a*, an adder **51** and a line **52** to the accumulator **25**. The appropriate coefficient C_n is accessed from a harmonic coefficient memory **53***a*, described in more detail below, under the direction of a memory address control **54***a* also receiving the signals t_{cp1} through t_{cp8} via the line **36**. The coefficient C_n is supplied to the multiplier **49***a* via a line **55***a*.

As indicated by the diagram of FIG. **2**, the first four low order 16-foot odd harmonics are calculated in the channel **24B** during the respective timing intervals t_{cp1} through t_{cp4}. These calculations are carried out in accordance with equation **2** above. To this end, the values $n'q(R/2)$ for $n'=1,3,5,7$ are established in a harmonic interval adder **56** during the respective timing intervals t_{cp1} through t_{cp4}.

The component $F_{16}^{(1)}$ is evaluated during the first interval t_{cp1}. The value $n'q(R/2) = q(R/2)$ is obtained in the adder **56** by gating the signal qR from the line **43** to a divide-by-two divider circuit **57** via a gate **58** enabled by the t_{cp1} signal. The output of the divider **57**, corresponding to the value $q(R/2)$ is entered into the harmonic interval adder **56** via the line **59**.

An address decoder **45***b* accesses from a sinusoid table **46***b* the value $\sin(\pi/W)[q(R/2)]$ corresponding to the argument $q(R/2)$ received from the harmonic interval adder **56** via an OR-gate **61**. The accessed sin value, supplied via a line **48***b*, is multiplied by the coefficient $C_n' = C_1'$ for the corresponding first odd **16**-foot harmonic by a multiplier **49***b*. The coefficient C_1' is obtained via a line **55***b* from a harmonic coefficient memory **53***b* accessed by a memory address control **54***b* also receiving the timing signals t_{cp1} through t_{cp8} via the line **36**. The multiplication product, representing the amplitude $F_{16}^{(1)}$ is supplied via a line **50***b* to the adder **51**. The adder **51** adds the component $F_{16}^{(1)}$ to the component $F_8^{(1)}$ which is concurrently evaluated in the channel **24A**. The sum is supplied via the line **52** to the accumulator **25**.

The next three 16-foot odd harmonics ($n'=3,5,7$) are calculated during the computation intervals t_{cp2} through t_{cp4}. At each such interval, the value qR from the line **43** is added to the contents of the harmonic interval adder **56** via a gate **62** enabled by the pulses t_{cp2} through t_{cp4} on the line **33**. Thus at time t_{cp2} the adder **56** will contain the value $n'q(R/2) = 3q(R/2) = (R/2) + qR$. Similarly, at intervals t_{cp3} and t_{cp4} the contents of the adder **56** will be $5q(R/2) = (R/2) + 2qR$ and $7q(R/2) = (R/2) + 3qR$ respectively. Conveniently, during the same intervals t_{cp2} through t_{cp4} the values qR, $2qR$ and $3qR$ already are present on the line **43** from the adder **40**.

The address decoder **45***b* and sinusoid table **46***b* operate as before to supply the designated sin values via the lines **48***b* to the multiplier **49** for multiplication by the corresponding harmonic coefficients C_3**440**, C_5' and c_7' respectively. The multiplication products provided to the line **50**b at the times t_{cp2}, t_{cp3} and t_{cp4} respectively represent the values $F_{16}^{(n')}$ for $n'=3,5,7$. These values are summed with the concurrently evaluated 8-foot components in the adder **51** and supplied to the accumulator **25** via the line **52**.

After the value $F_{16}^{(7)}$ has been evaluated, the harmonic interval adder **56** is cleared by the t_{cp4} signal slightly delayed in a delay unit **63**. The contents of the adder **56** remains set at zero for the remainder of the amplitude computation cycle.

The four high order, even harmonics of the 8-foot series ($n=10,12,14,16$) are calculated in the processing channel **24B** during the calculation intervals t_{cp5} through t_{cp8}. To this end, a gate **65** enabled by the timing signals on the line **35** supplies the value nqR from the line **47** to a multiply-by-two multiplier circuit **66**. The output 2nqR from the multiplier **66** is provided via a line **67** and the OR-gate **61** to the address decoder **45**b.

Recall that at time t_{cp5} the contents of the harmonic interval adder **42** is $nqR = 5qR$. Accordingly, at the interval t_{cp5} the argument $2nqR = 10qR$ will be provided via the OR gate **61** to the decoder **45***b* and the sinusoid table **46***b*. This is exactly the argument ($10qR$) necessary to calculate the 10th 8-foot harmonic component. The sinusoid table **45***b*, the multiplier **49***b* and the harmonic coefficient memory **53***b* operate as above described to provide the value $F_8^{(10)}$ via the line **50***b* to the adder **51.**

Similarly, at the time intervals t_{cp6} through t_{cp8} the values $6qR$, $7qR$ and $8qR$ are present on the line **47.** Accordingly, the arguments supplied to the decoder **45***b* will be $12qR$, $14qR$, and $16qR$ respectively. Accordingly, the components $F_8^{(n)}$ for n=12, 14, 16 will be calculated in the processing channel **24**B.

In this manner the computor organ **20** calculates exactly those components shown as solid lines in FIG. **1.** The generated waveshape, the sample point amplitude of which are obtained in the accumulator **25,** has a harmonic spectra characteristic of combined footage. The resultant sounds produced by the computor organ **20** of FIG. **3** have the tonal quality of simultaneously selected **8**-foot and 16-foot stops.

The specific voicing of the produced sounds will depend on the stored values of the harmonic coefficients C_n and C_n'. This of course is a design choice, however the following Table I lists appropriate values of C_n and C_n' which will simulate a diapason voice. The values C_1 through C_8 are stored in the memory **53***a*; the remaining coefficients listed in Table I are stored in the memory **53***b*.

TABLE I

Harmonic coefficient	Combined 8-foot and 16-foot diapason voice (Relative amplitude)	(Decibel equivalent) db.	Harmonic coefficient memory	Interval during which storage location is accessed
C_1	127	0	53a	t_{cp1}
C_2	71	−5	53a	t_{cp2}
C_3	90	−3	53a	t_{cp3}
C_4	36	−11	53a	t_{cp4}
C_5	23	−15	53a	t_{cp5}
C_6	25	−14	53a	t_{cp6}
C_7	8	−24	53a	t_{cp7}
C_8	8	−24	53a	t_{cp8}
C_{10}	4	−31	53b	t_{cp5}
C_{12}	2	−38	53b	t_{cp6}
C_{14}	1	−42	53b	t_{cp7}
C_{16}	1	−42	53b	t_{cp8}
C'_1	127	0	53b	t_{cp1}
C'_3	90	−3	53b	t_{cp2}
C'_5	23	−15	53b	t_{cp3}
C'_7	8	−24	53b	t_{cp4}

The frequency numbers R stored in the memory **39** are related to the fundamental frequencies of the musical notes produced by the computor organ **20,** to the computation time interval t_x, and to the number of amplitude sample points N for the note of highest fundamental frequency f_H produced by the organ. For example, if the frequency number R for such note of highest frequency is selected as unity, then with a computation time interval t_x given by $t_x=8t_{cp} = 1/Nf_H$, exactly N sample point amplitudes will be computed for that note.

The values R for notes of lower frequency readily can be ascertained, knowing that the frequency ratio of any two contiguous notes in an equally tempered musical scale is $\sqrt[12]{2}$. In general, the frequency numbers R for notes other than that of highest frequency f_H will be non-integers.

By way of example, the following Table II lists the frequency and frequency number R for each note in octave six. The note C_7 (the key of C in octave 7) is designated as the note of highest fundamental frequency produced by the computor organ **20,** and hence is assigned the frequency number R of unity. In this example, N=2W=32 sample points are computed for the note C_7, this value of N being satisfactory for accurate synthesis for an organ pipe or most other musical sounds.

TABLE II

NOTE	PREQUENCY (Hz)	R
C_7	2093.00	1.0000
B_6	1975.53	0.9443
$A\#_6$	1864.66	0.8913
A_6	1760.00	0.8412
$G\#_6$	1661.22	0.7940
G_6	1567.98	0.7494
$F\#_6$	1479.98	0.7073
F_6	1396.91	0.6676
E_6	1318.51	0.6301
$D\#_6$	1244.51	0.5947
D_6	1174.66	0.5613
$C\#_6$	1108.73	0.5298
C_6	1046.50	0.5000

Using the modification of FIG. **5,** the computor organ **20** (FIG. **3**) can produce other footage stops such as those having the spectra of FIGS. 4A through 4F. Separate memories store the harmonic coefficients for each stop; in each memory the coefficient value zero is stored for all harmonic absent in the spectra of the associated stop. A switching arrangement permits selction by the musician of any one or more footage stops.

In the embodiment of FIG. **5**, the harmonic coefficient memories **53***a*, **53***b* (FIG. **3**) are replaced by two sets of memories **70***a*, **70***b*, accessed by the respective memory address control units **54***a'*, **54***b'* which receive the timing pulses t_{cp1} through t_{cp8} on the line **36.** Harmonic coefficients are supplied to the harmonic amplitude multipliers **49***a*, **49***b* via stop selection switches (stop tabs) designated ST_{16}, ST_8, ST_4, ST_2, ST_1, $ST_{2\ 2/3}$ and $ST_{1\ 3/5}$ wherein the subscript designates the footage of the respective stop tab. The coefficients are combined by appropriate OR gates **71, 72***a*, **72***b* and adders **73***a*, **73***b*, **74***a*, **74***b*, **75***a*, **75***b* and supplied to the multipliers **49***a*, **49***b* via the respective lines **55***a* and **55***b*. This arrangement permits selection of any individual footage stop, or any combination of such stops.

If the stop switch ST_8 alone is closed, the computor organ **20** will generate an 8-foot voice having the incomplete harmonic spectra shown in solid lines in FIGS. **1** and **4**A. To this end, the memory **81**a contains coefficient values C_1 through C_8 inclusive. These values are supplied to the multiplier **49***a* via the adder **73***a*, the second input of which remains at zero since no stop tab other than ST_8 is selected. The memory **81**b contains the harmonic coefficients C_{10}, C_{12}, C_{14} and C_{16} stored in locations accessed during the successive time intervals t_{cp5} through t_{cp8}. The memory **81**b stores the value zero in those locations accessed at times t_{cp1} through t_{cp4}. Thus during the intervals t_{cp1} through t_{cp4} the value zero is supplied from the memory **81**b via the OR-gate **71** and the adder **73**b to the multiplier **49**b. Accordingly, the channel **24**B makes no contribution to the computed waveshape during those time intervals when, were a 16-foot stop also selected, the first four low order, 16-foot odd harmonics would be computed. During the intervals t_{cp5} through t_{cp8}, the coefficients C_{10}, C_{12}, C_{14} and C_{16} respectively are supplied to the multiplier **49**b, so that the corresponding 10th, 12th, 14th and 16th 8-foot harmonics are evaluated. The resultant waveshape of the harmonic spectra of FIGS. **1** and 4A, characteristic of an 8-foot voice.

To generate a combined 8-foot and 16-foot voice using the modification of FIG. **5**, the stops ST_8 and ST_{16} both are closed. The memories **81**a, **81**b provide the coefficients described above, resulting in production of the incomplete 8-foot spectra of FIG. **1.** A memory **82**b stores the harmonic coefficient values C_1', C_3', C_5' and C_7' in locations accessed during the successive intervals t_{cp1} through t_{cp4}. These values are supplied via the OR-gate **71** and the adder **73**b to the multiplier **49**b. Accordingly, when both the ST_8 and ST_{16} stop tabs are selected, the memories **81**a, **81**b and **82**b together function exactly like the memories **53**a, **53**b of FIG. **3**, and the combined 8-foot and 16-foot spectra of FIG. **1** is generated.

A 16-foot spectra alone can be generated by closing only the switch ST_{16}. Again, the memory **82**b provides the coefficients appropriate to generate the first four 16-foot odd harmonics. The first eight 16-foot even harmonics are generated with coefficients provided by the memory **81**a. The resultant 16-foot spectra will correspond to that shown in the lower portion of FIG. **1**, except that there will be no harmonic higher than the 16th (n'=16). A 4-foot voice is produced when the switch ST_4 is closed. The memories **83**a, **83**b contain the values C_n for all even values of n between n=2 and n=16. As indicated in Table III below, these values are stored in locations accessed during the calculation intervals used for production of the corresponding components of the 8-foot spectra of FIG. 4A. All other positions of the memories **83**a, **83**b store zeros. When the 4-foot stop ST_4 is selected, the computor organ **20** will produce a sound having the harmonic spectra of FIG. 4B.

Similarly, a 2-foot, 1-foot, 2⅔-foot or 1 3/5-foot voice is produced when the corresponding switch ST_2, ST_1, $ST_{2\ 2/3}$ or $ST_{1\ 3/5}$ is closed. Table III also lists the contents of the harmonic coefficient memories **84**a through **87**b used with these footage stops. The coefficient values given in Table III are illustrative of a diapason voice; other values may be used to provide different voicing. However, those stored zero valued coefficients should remain zero to insure generation of spectra like those of FIGS. 4C through 4F.

When the 2 ⅔-foot stop is selected, only those components shown in solid lines in FIG. 4E are generated. The third and fifth harmonics, corresponding in frequency to the eighth (n=8) and 16th (n=16) harmonics of the 8-foot spectra, are not produced. Similarly, when the 1 3/5-foot stop is selected, the third harmonic (corresponding to the 15th 8-foot harmonic) is not produced. These missing components are designated by broken lines in FIGS. 4E and 4F respectively, and correspond to components which are absent in the incomplete 8-foot spectra (FIG. 4A) generated by the computor organ **20.**

TABLE III

Footage	Harmonic Coefficient Memory	Stored Harmonic Coefficient*	Typical Coefficient Value (Diapason)	Interval During Which Storage Location is Accessed
4-foot	**83**a	C_2	127	t_{cp2}
		C_4	71	t_{cp4}
		C_6	90	t_{cp6}
		C_8	36	t_{cp8}
	83b	C_{10}	23	t_{cp5}
		C_{12}	28	t_{cp6}
		C_{14}	8	t_{cp7}
		C_{16}	8	t_{cp8}
2-foot	**84**a	C_4	127	t_{cp4}
		C_8	71	t_{cp8}
	84b	C_{12}	90	t_{cp6}
		C_{16}	36	t_{cp8}
1-foot	**85** a	C_8	127	t_{cp8}
	85b	C_{16}	71	t_{cp8}
2 ⅔-foot	**86**a	C_3	127	t_{cp3}
		C_6	71	t_{cp6}
	86b	C_{12}	36	t_{cp6}
1 3/5-foot	**87**a	C_5	127	t_{cp5}
	87b	C_{10}	71	t_{cp5}

* All other stored harmonic coefficient values are zero.

As noted earlier, the shorter footage stops often are used to enhance certain harmonics of another stop. This is illustrated by the spectra of FIGS. **4**A and **4**F for the case when an 8-foot and 1 3/5-foot stop simultaneously are selected. In this instance, the fifth and 10th 8-foot harmonics are emphasized. These harmonics have the resultant amplitudes shown by broken lines **90, 91** in FIG. **4**A, and specified by the sums of the harmonic coefficients of both selected stops.

For the combined 8- and 1 3/5-foot stop, at the time t_{cp5} separate non-zero harmonic coefficients are accessed from both the memories **81**a and **87**a. The latter coefficient is supplied via the OR-gate **72**a and the adders **75**a, **74**a to the adder **73**a wherein it is summed with the coefficient accessed from the memory **81**a. The sum is supplied via the line **55**a to the multiplier **49**a, so that the calculated fifth (n=5) harmonic component has the resultant amplitude shown by the line **90** in FIG. **4**A.

Similarly, in channel **24**B at time t_{cp5} non-zero coefficient values are accessed from both the memories **81**b and **87**b. The latter is supplied via the OR-gate **72**b and the adders **75**b, **74**b to the adder **73**b where it is summed with the coefficient accessed from the memory **81**b. The sum is supplied via the line **55**b to the multiplier **49**b. Thus the evaluated 10th 8-foot harmonic has the enhanced amplitude shown by the broken line **91** in FIG. **4**A. At all times other than t_{cp5}, zero-valued coefficients are accessed from the 1 3/5-foot memories **87**a, **87**b so that the other harmonics of the 8-foot series are not enhanced.

The computor organ **20** of FIG. **3** readily may be implemented using conventional microelectronic integrated circuits (IC's). Thus the frequency number memory **39** may comprise an IC read-only memory programmed to contain the frequency numbers R listed in Table II above. A useful IC read-only memory is the Signetics type **8223** which is user programmable and includes addressing circuitry. Such an IC also may be used as the harmonic coefficient memory **53**a, **53**b **70**a or **70**b, with the self-contained addressing circuitry serving as the associated memory address decoder **54**a, **54**b, **54**a', or **54**b'. Typical stored harmonic coefficient values are listed in Tables I and III.

The adders **40, 42** and **56** may be implemented using conventional IC adders; such circuits include the Signetics 8260 arithmetic logic element, the Signetics 8268 gated full adder, and the Texas Instruments SN 5483 and SN 7483 4-bit binary full adders. In FIG. **3**, the adjectives "note interval" and "harmonic interval" are used to indicate the function of the adder in the computor organ **20**. Thus the contents *qR* of the adder **25** designates the sample point interval at which the note amplitude presently is being evaluated. Similarly, the adders **42** and **56** contain the values *nqR* specifying the sample point intervals of the 8-foot harmonics being evaluated in the respective channels **24**A and **24**B.

The accumulator **25** may comprise IC adders connected as shown e.g., in the standard text by Ivan Flores entitled "Computor Logic," Prentice-Hall, 1960. Each sinusoid table **46***a*, 46*b* and its address decoder **459**, **45***b* may comprise an IC read-only memory containing sinusoid values with appropriate resolution D. Memories preprogrammed with sinusoid values are available commercially, as typified by the Texas Instruments TMS 4405 integrated circuit. The multipliers **49***a*, **49***b* are conventional, the adjective "harmonic amplitude" indicating that the circuit multiplies the sin value (from the line **48***a* or **48***b*) by the appropriate harmonic coefficient (from the line **55***a* or **55***b*) to obtain as a product the amplitude of the harmonic component then being calculated in the channel **24**A, **24**B containing the multiplier. Likewise, the remaining components of the computor organ **20** (FIG. **3**) are conventional.

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

1. In an electronic musical instrument of the type wherein the amplitudes of a waveshape are computed at regular time intervals t_x from stored harmonic coefficients, musical notes being produced from said computed amplitudes as said computations are carried out, the improvement comprising:

first means for calculating an incomplete set of harmonics of a first footage voice from said stored coefficients during certain calculation subintervals within each regular interval t_x,

second means for calculating, during other calculation subintervals within each such interval t_x, harmonics associated with a voice of footage different from said first footage, and third means for obtaining each waveshape amplitude by combining all components calculated during each time interval t_x.

2. A musical instrument according to claim **1** wherein said first footage voice is an 8-foot stop, wherein said different footage voice is a 16-foot stop, and wherein said second means includes a memory storing a set of harmonic coefficients for said 16-foot stop, said set including non-zero coefficients only for odd 16-foot harmonics, calculation of both said 8-foot incomplete set of harmonics and said odd 16-foot harmonics resulting in musical notes having a combined 8-foot and 16-foot tonal quality.

3. A musical instrument according to claim **2** wherein no longer footage odd harmonics are calculated, and including means for calculating less than all harmonics of said incomplete set of first footage, the resultant musical notes having the tonal quality of a stop of footage shorter than said first footage.

4. A musical instrument according to claim **3** including;

a first memory means, connected to provide to said first means a set of harmonic coefficients associated with said first footage voice and

a second memory means connected to provide to said first means a selected separate set of harmonic coefficients associated with another voice of shorter footage, the spectra of said shorter footage voice including only some harmonics of said first footage, said set of shorter footage coefficients including non-zero valued coefficients only for said some harmonics, all other coefficients being zero valued, so that during each regular time interval t_x, when said selected separate set of coefficients is provided to said first means, only those first footage components also included in the spectra of said selected shorter footage voice are calculated.

5. A musical instrument according to claim **4** further comprising means for combining the stored harmonic coefficients for said first set and the stored harmonic coefficients for at least one other shorter footage voice for use in the harmonic component calculations, said other shorter footage voice thereby enhancing the amplitude of certain components in said first set.

6. A musical instrument according to claim **1** and having parallel processing channels, certain harmonic components of said incomplete set being calculated in one of said channels during the same subintervals that certain of said longer footage odd harmonics are calculated in another of said channels.

7. A musical instrument providing combined footage, comprising:

parallel processing channels for calculating within a regular time interval t_x first and second subsets of Fourier components associated with the amplitude of a musical waveshape at a certain sample point, said first subset including harmonic components of a first footage which correspond to even harmonics of a second footage of lower fundamental frequency, said second subset including odd harmonic components of said second footage, said first and second footages respectively being 8-foot and 16-foot, each 8-foot component $F_8^{(n)}$ being calculated according to the equation

$$F_8^{(n)} = C_n \sin(\pi/W)\, nqR$$

wherein C_n is a coefficient associated with the n^{th} 8-foot harmonic, wherein R is a frequency number associated with each note selected for production by said instrument, wherein $q=1,2,3\ldots$ so that qR designates said certain sample point and wherein W is the total number of components evaluated to obtain each amplitude, each 16-foot component being calculated according to the equation

$$F_{16}^{(n)} = C_n' \sin(\pi/W)\, n'q(R/2)$$

wherein C_n' is a coefficient associated with the n^{th} 16-foot harmonic component,

note selection means for providing a value R associated with a selected note,

means for providing to said first channel the values nqR for certain values of n within each regular time interval t_x

means for providing to said second channel values nqR for certain non-consecutive values of n and values $n'q(R/2)$ for certain odd values of n',

accumulator means for combining the Fourier components calculated by said processing channels during each time interval t_x to obtain the wave-shape amplitude at said certain sample point,

control means for causing said processing channels and said accumulator means to perform said calculating and combining operations repetitively for successive sample points during successive time intervals t_x, and

converter means for producing musical sounds from said obtained amplitudes as said calculating and combining are carried out in real time, said sounds having a tonal quality characteristic of combined footage,

and wherein each processing channel comprises:

a memory storing harmonic coefficients associated with components calculated in that channel,

means for obtaining the values sin $(\pi/W)\ nqR$ and sin $(\pi/W)\ n'q(R/2)$ corresponding to the value of the argument nqR and $n'q(R/2)$ respectively provided to that channel, and

a multiplier for multiplying the appropriate harmonic coefficient from said memory means by said obtained sin value and providing the product to said accumulator means.

8. A musical instrument according to claim **7** wherein for said first channel said certain values of n are n=1,2, . . . 7,8, and wherein for said second channel said certain non-consecutive values of n are n=10,12,14,16 and wherein said certain odd values of n' are n'=1,3,5,7.

9. A musical instrument according to claim **7** wherein all stored values of C_n' are zero so that no 16-foot odd harmonics are generated, and further comprising means for implementing stops of other footage comprising:

separate memory means storing harmonic coefficients associated respectively with said other footage stops, and

stop selection means for accessing from said separate memory means coefficients associated with selected other footage stops and for providing said accessed coefficients to said multipliers.

10. A musical instrument according to claim **6** wherein said other footage associated coefficients are used instead of said 8-foot coefficients C_n, said instrument then producing an other than 8-foot voice.

11. A musical instrument according to claim **9** wherein said other footage associated coefficients are used in addition to said 8-foot coefficients, said instruments then producing an 8-foot voice having certain enhanced harmonics.

12. An instrument according to claim **7** wherein instead of a combined 8-foot and 16-foot voice, a combined voice consisting of an 8-foot stop and another shorter footage stop is produced, comprising:

a. means for disconnecting from one processing channel the harmonic coefficient memory containing the 16-foot harmonic coefficients,

b. a storage device for storing a set of harmonic coefficients for another voice of shorter footage, said set including non-zero valued coefficients only for components corresponding to certain harmonics of said first subset, all other coefficients being zero-valued, and

c. switching means for connecting to said parallel processing channels said storage device and the memory containing said first subset of 8-foot harmonic coefficients, so that during each regular time interval t_x those 8-foot harmonic components also included in the spectra of said shorter footage voice are enhanced.

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