

June 20, 1967

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3,327,043

MULTIPLE SPEAKER SOUND OUTPUT SYSTEM FOR
REDUCING INTERMODULATION DISTORTION

Filed March 12, 1964

7 Sheets-Sheet 1

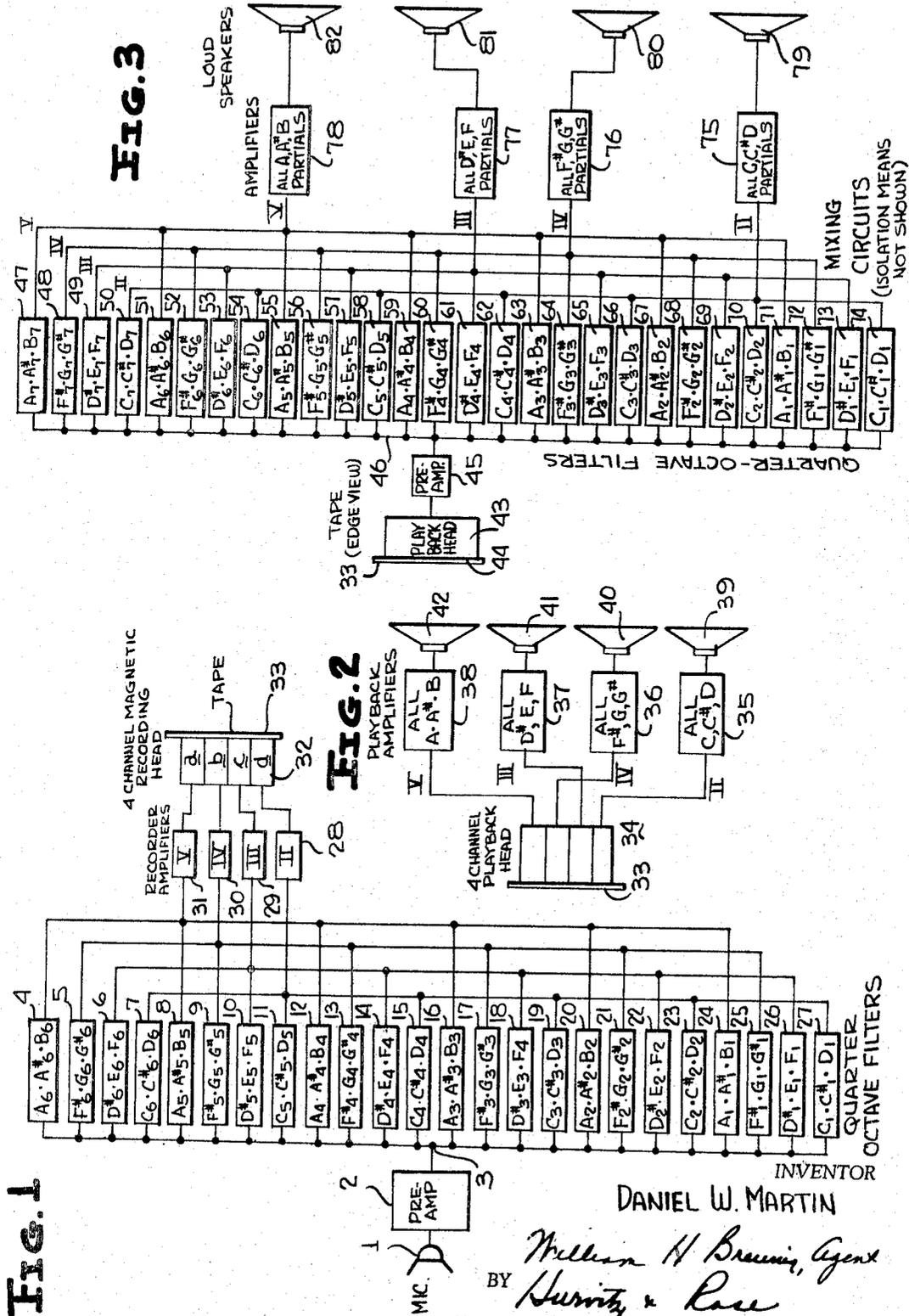


FIG. 1

FIG. 2

FIG. 3

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FIG. 4

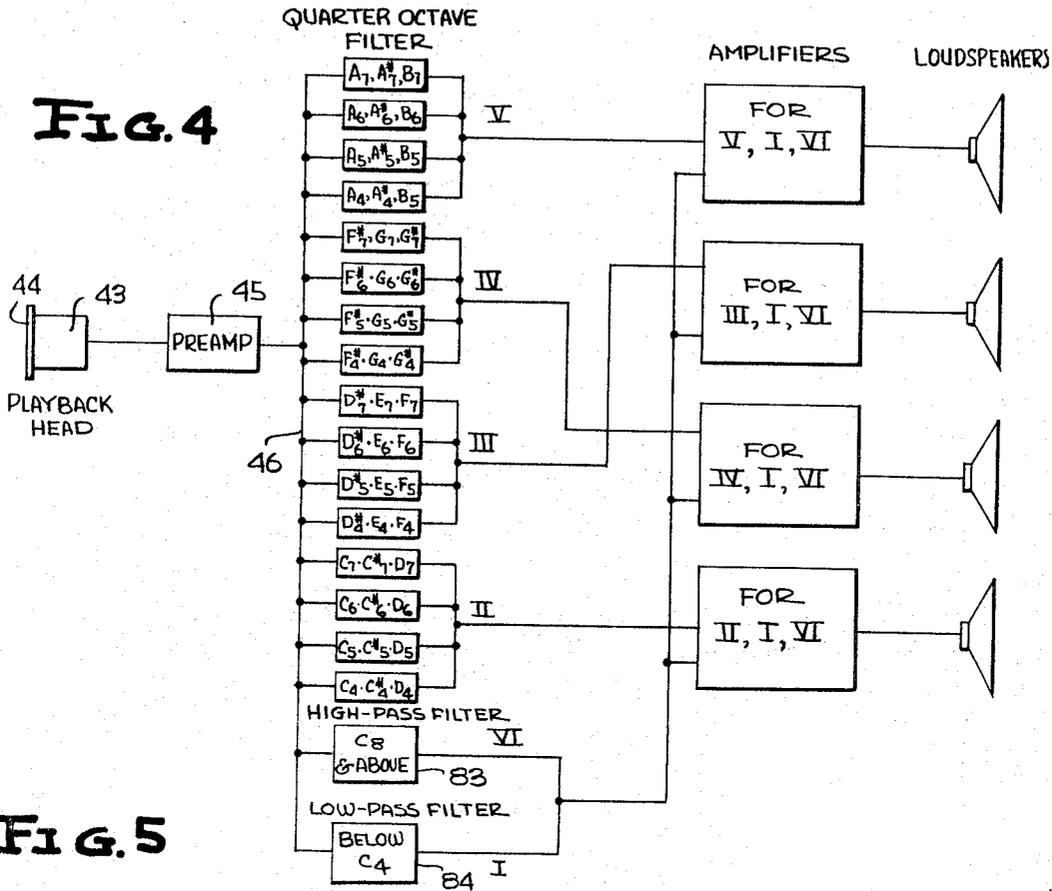
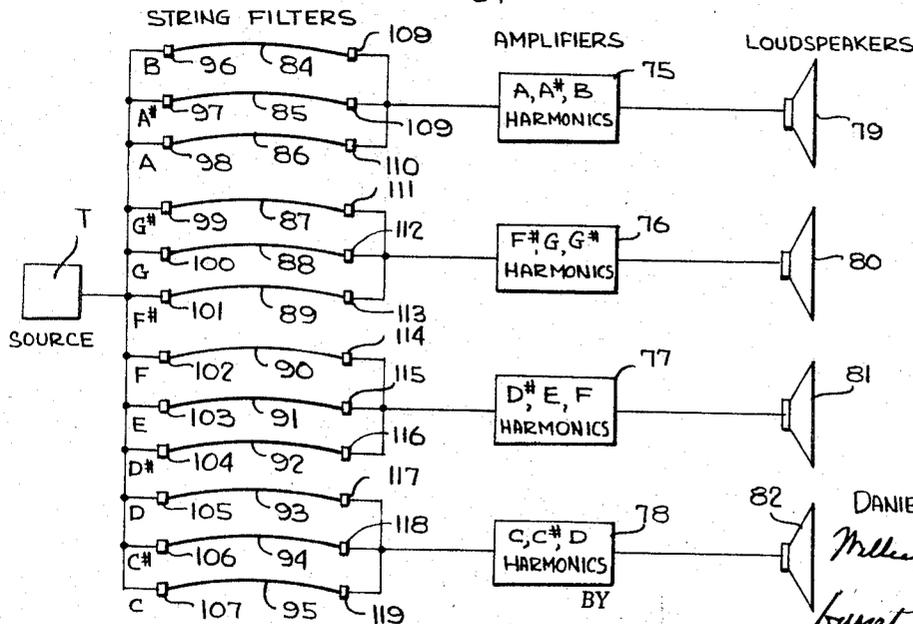


FIG. 5



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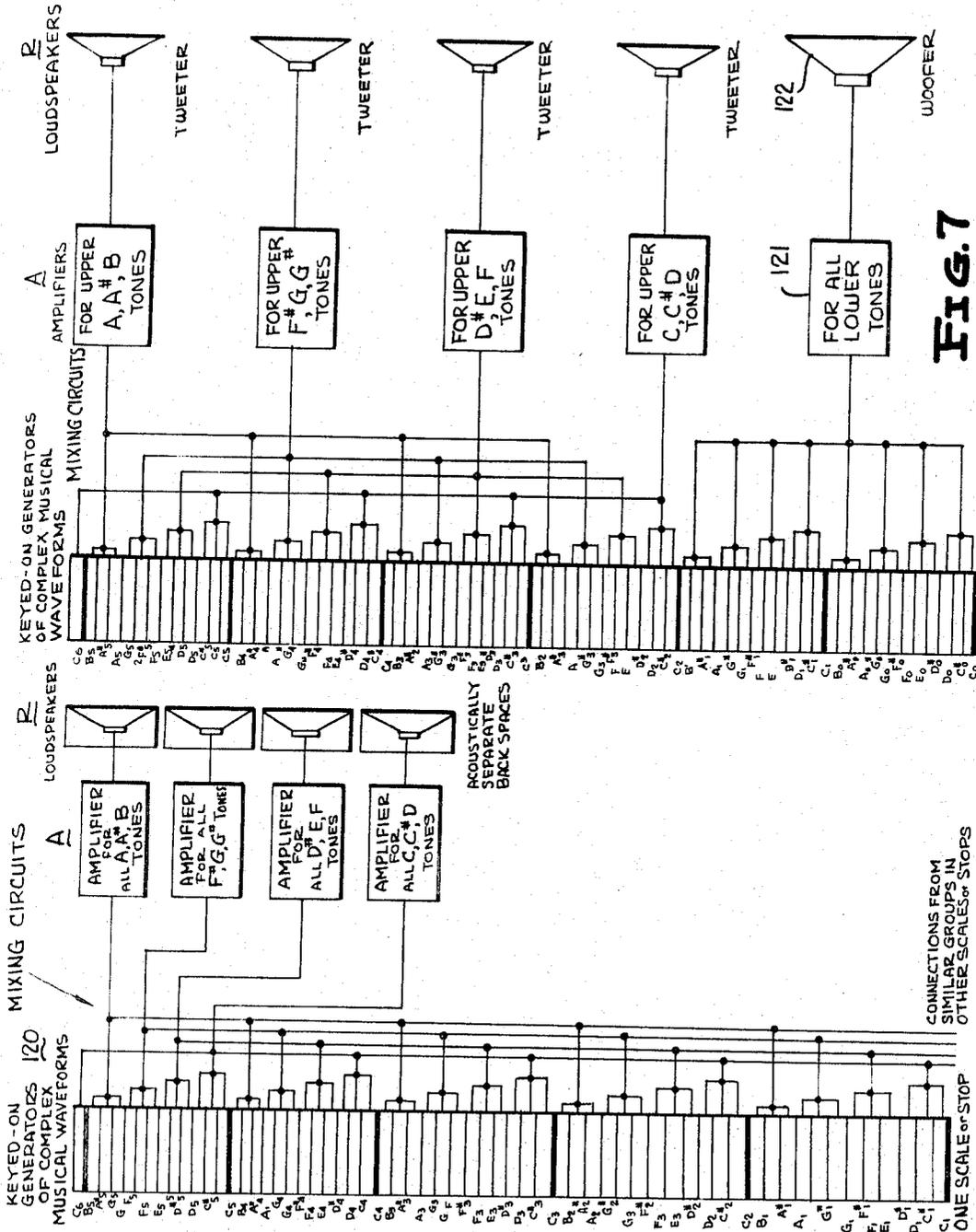


FIG. 7

FIG. 6

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Fig. 12

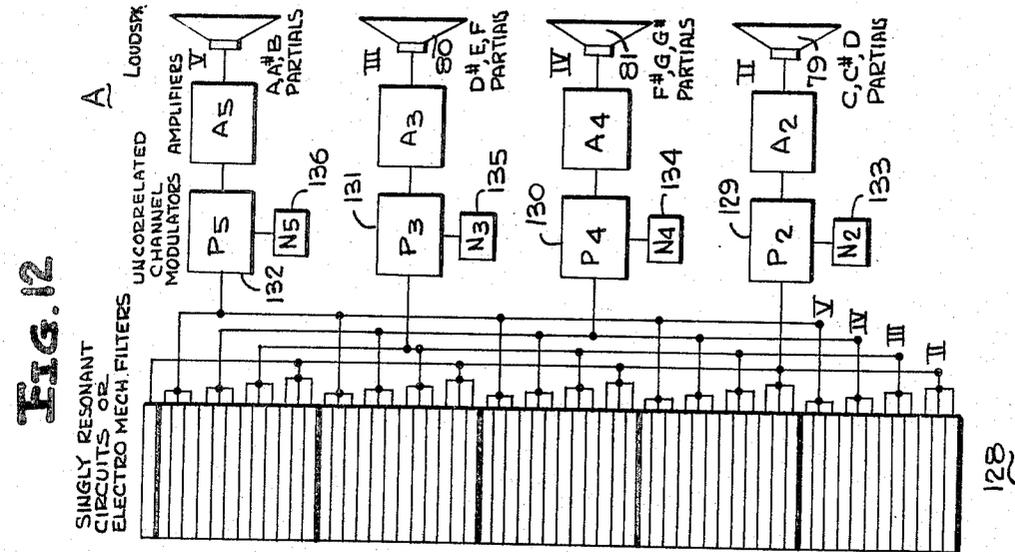
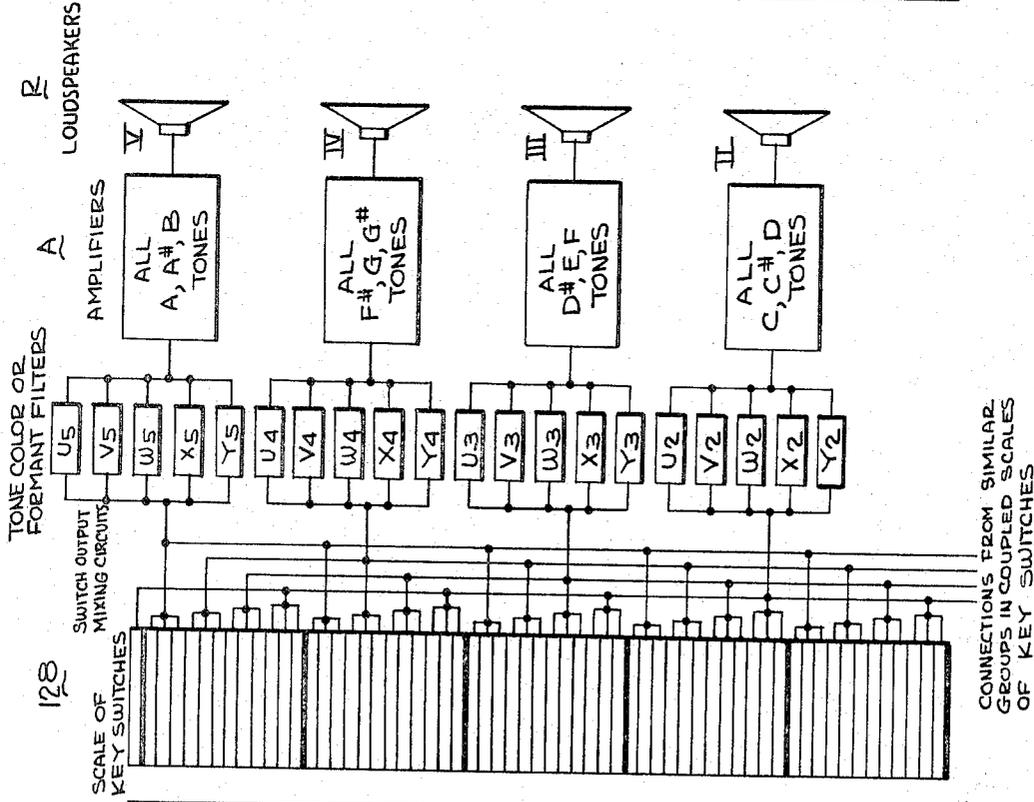


Fig. 8



INPUTS FROM CONTINUOUS TONE GENERATORS

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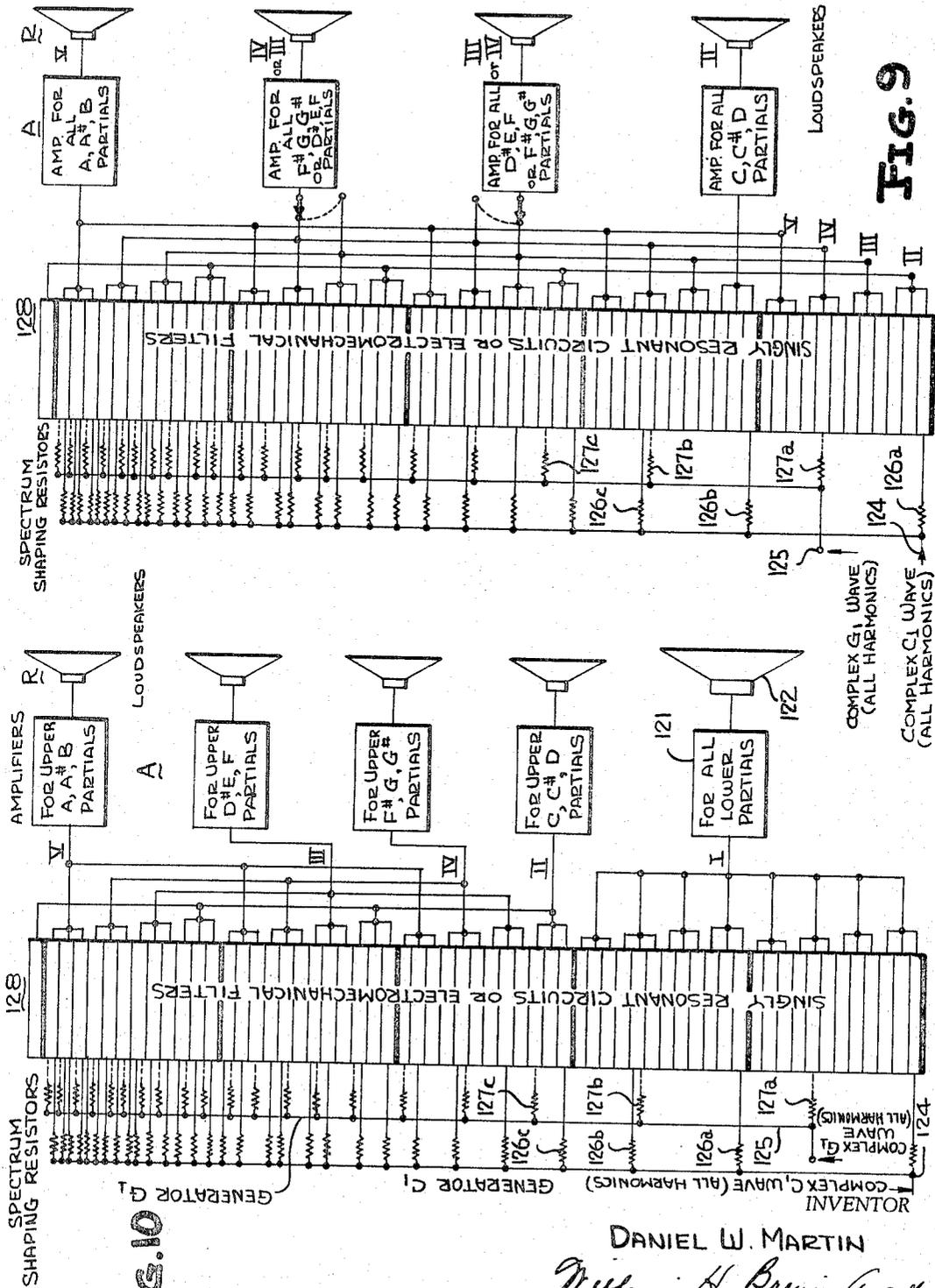


FIG. 9

FIG. 10

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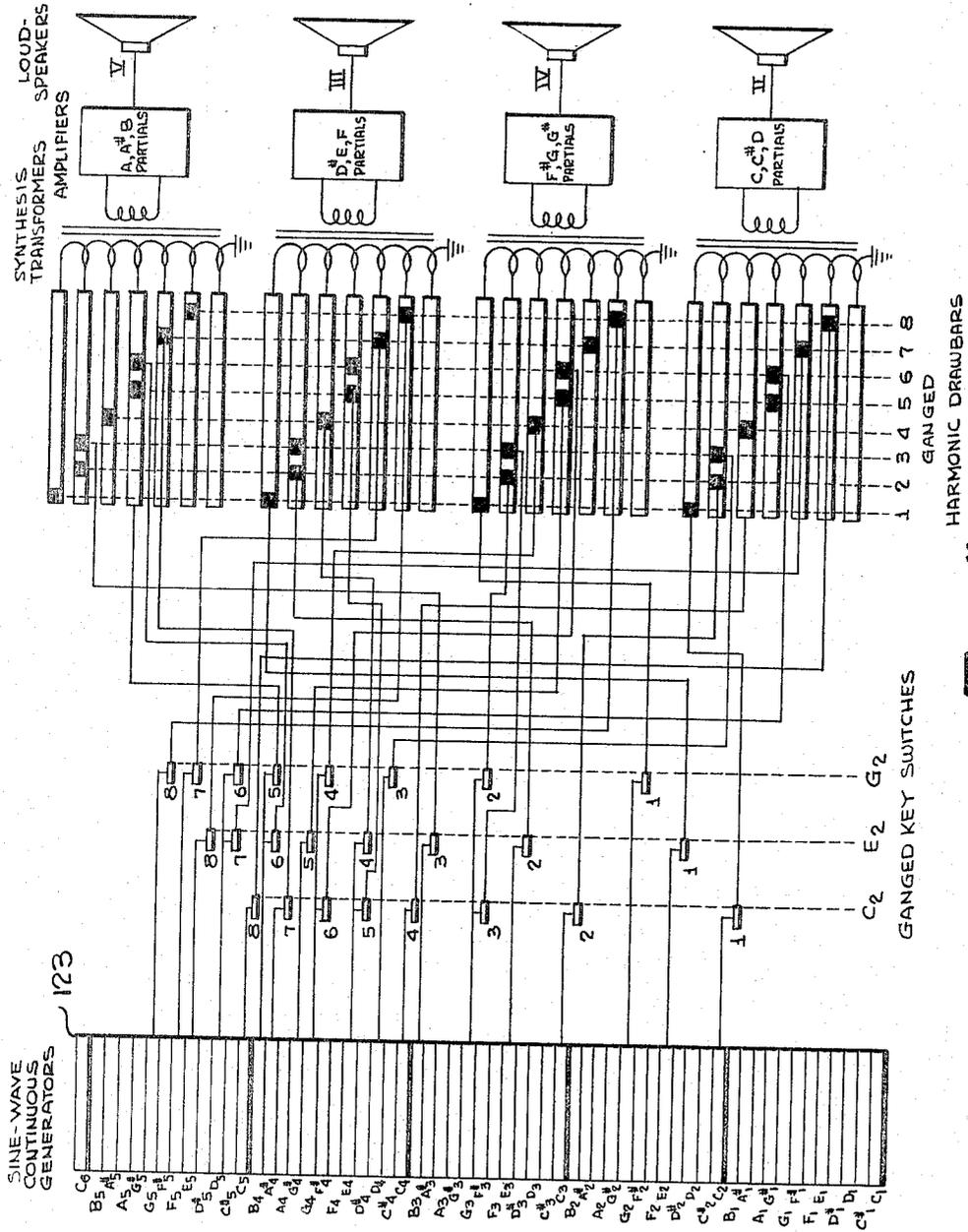


FIG. 11

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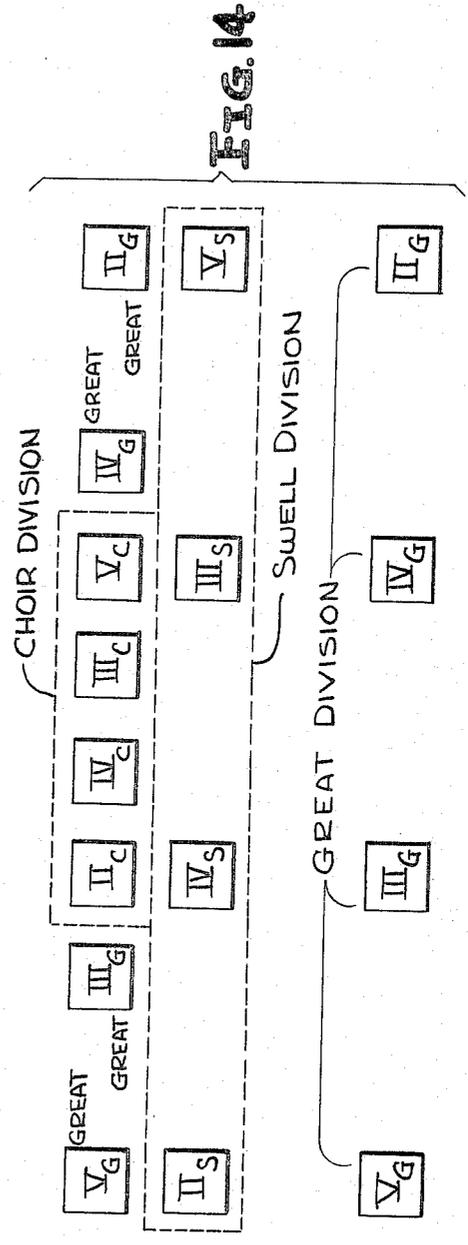
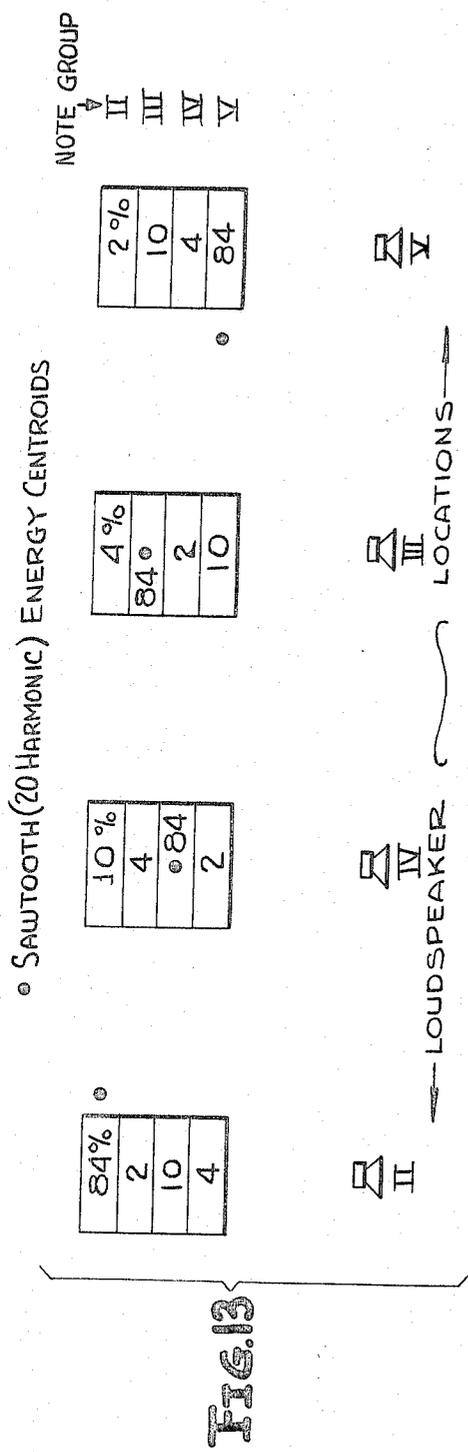
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MULTIPLE SPEAKER SOUND OUTPUT SYSTEM FOR REDUCING INTERMODULATION DISTORTION

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15 Claims. (Cl. 84—1.01)

The present invention relates generally to systems for processing musical sounds, in its electronic production, recording and/or reproduction, and more particularly to systems for reduction of intermodulation distortion produced by simultaneous tones subsisting in relatively small sub-bands of the audio frequency band, while enhancing the musical quality of the simultaneous tones.

A most important limitation of present high-fidelity music amplification systems is the necessity to reproduce simultaneously from the same amplifier and loudspeaker tones lying in the same general region of the audio-frequency spectrum. In systems of high quality it has been customary to divide the entire audio frequency range into two, three, or even four broad bands, so as to avoid intermodulation distortion of the type produced by simultaneous tones of widely different frequency. However the other principal form of undesirable intermodulation distortion (that produced by simultaneous tones within a few octaves of each other), has continued to degrade sound reproduction. These effects are particularly noticeable in the medium and high-frequency ranges of sound, because difference frequencies in intermodulation distortion are much more audible than the summation components. The sense of hearing is rather insensitive to weak sounds of very low frequency. Hence the tones which (in combination) generate disturbing distortion must be high enough in frequency for their difference to be in the order of 100 cycles or more.

Another problem in sound reproduction systems, especially in large auditoriums, has been to retain the desirable directional characteristics designed into a loudspeaker of limited power-delivering capacity, when the power requirements substantially exceed the unit's capacity. The obvious practice is to use a large number of similar units electrically in parallel, and to neglect the spectral degradation resulting from interference effects between waves from different units, and the highly directional "beaming" effect produced by a parallel array of similar units.

When music is to be produced (rather than reproduced) electro-acoustically, similar problems exist. One of the inherent economic advantages of electronic organs over pipe organs, for example, is that the tones can all be radiated acoustically from the same sound source. However, there are disadvantages from a tonal standpoint which are inherent in the single sound-source method of tone radiation, such as (1) intermodulation distortion, (2) a deficiency in apparent size of the musical sound source (in comparison to the historical instrument), and (3) a lack of change in sound localization when different notes in the scale are played. It is possible, of course, to have different notes of the same pitch come from audibly different locations, e.g. when different loudspeakers are used for different divisions of the organ, but this does not provide for any motion of the sound source when the note changes within the division.

One electronic organ system method which is used to increase the apparent physical size of the sources of sound is to use multiple sources in parallel. As in sound reproduction systems, this tends to "beam" the sound toward the listeners more than a single source would. This is highly undesirable for organ music. Another expedient is to orient the sound sources toward reflecting surfaces,

so as to increase the ratio of reflected-to-direct sound. Installing the sources in a moderately reverberant tone chamber coupled to the auditorium is still another approach. These methods reduce acoustical efficiency, and reduce the tonal definition required for full appreciation of musical subtleties such as transient effects in the tone.

Accordingly it is a principal object of my invention to produce or reproduce musical sounds with a minimum of intermodulation distortion.

A further object is to provide a broad smooth directional characteristic throughout the musical frequency range, so that the tonal spectra at all normal listening positions will closely resemble each other, and will also be similar to the spectrum of the total power radiated from the loudspeakers. This will tend to make the direct sound and the generally reflected sound similar in timbre.

A further object is to provide motion for the musical source as the frequency changes, and to provide spread for the musical source when various non-octavely related frequencies are present.

A further object is to provide a system for musical spatial modulation effects which are a rapidly changing function of frequency, i.e. which vary greatly within the span of an octave.

The key to the solution of the above problems and to the attainment of the above objects is to be found in the nature and composition of musical sound, and in an acoustically novel subdivision of the audible frequency range. Simultaneous *octavely* related tones occur rather frequently in music. Their intermodulation products are not very serious musically because the distortion products of octaves are also octavely related to the original tones. Consequently they are very difficult to distinguish from the original combination of tones. An ideal radiation system for musical tone, from an intermodulation distortion standpoint, would be one in which only octavely related tones are radiated together. Only in very large sound systems would this be economically feasible. Another musical factor, which is pertinent to my invention, is that the frequency of occurrence of closely adjacent musical tones in combination is very small. When such adjacent tones (e.g. E and F in the musical scale) are played, the dissonance effects experienced by the listener overshadow intermodulation distortion effects which, by comparison, are minor. Furthermore the more nearly adjacent are the tones played in combination, the lower the difference frequency becomes and (because the ear is quite insensitive to low frequencies) the less audible and objectionable the difference tones will be.

The above described combination of factors makes it advantageous to combine the ideal twelve octavely related groups of musical tones into six, four, or even three groups, and thus effect a reasonable compromise between the requirements for low intermodulation distortion and low cost. Combination into three groups is not too advantageous, because minor thirds are rather common intervals, and are quite consonant in comparison to major second intervals, which are the largest combined intervals (short of an octave) which will occur when there are four major groups of octavely related tones. Electronic and electroacoustical systems designed along these principles of frequency-range division and recombination may be described by the term "octaphonic." There are numerous other principles and refinements in the present invention, which will become apparent as the details are disclosed.

Other objects, advantages and features of the invention will also become more fully apparent from the following description of preferred embodiments thereof, taken in conjunction with the appended drawings, in which:

FIGURE 1 is a block diagram of an octaphonic system of recording, according to the invention;

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FIGURE 2 is a block diagram of a playback system using with the system of FIGURE 1;

FIGURE 3 is a block diagram of a system for reproducing octaphonically music derived from a conventional one track record;

FIGURE 4 is a block diagram of a modification of the system of FIGURE 3, wherein simplifications have been effected;

FIGURE 5 is a block diagram of a modification of the system of FIGURE 3 employing relatively few multiply resonant filters in place of many singly resonant filters;

FIGURE 6 is a block diagram of a system employing the octaphonic principle in a musical instrument which generates tone forms directly;

FIGURE 7 is a block diagram of a simplified modification of the system of FIGURE 6;

FIGURE 8 is a block diagram of a formant type of electronic musical instrument employing the octaphonic principle;

FIGURE 9 is a schematic block diagram of a resonator type of electronic musical instrument employing the octaphonic principle;

FIGURE 10 is a block diagram of a simplification of the system of FIGURE 9;

FIGURE 11 is a block diagram of a harmonic synthesis type of electronic musical instrument employing the octaphonic principle;

FIGURE 12 is a block diagram of a space modulation system for octaphonic sound production or reproduction equipment;

FIGURE 13 is a block diagram showing the locations of complex tonal centroids relative to locations of the loudspeakers in an octaphonic system; and

FIGURE 14 illustrates an exemplary physical arrangement of the loudspeakers in an installation of a multi-manual electronic organ of an octaphonic type.

In sound recording and playback systems it is generally possible to provide microphones and pre-amplifiers with remarkably good linearity of response, so that one need not be particularly concerned with intermodulation distortion in the low-level part of the recording system. However, the recorder amplifiers, the heads, and the medium itself may introduce audible distortion products, and frequently do. Consequently it is highly desirable, if possible, to apply the octaphonic method of frequency-range division ahead of the recorder amplifiers, as shown in FIGURE 1.

In the system of FIGURE 1, sound is picked up by microphone 1. The microphone output signal is amplified by pre-amplifier 2, from which the amplified output is supplied through common input 3 to a set of quarter-octave filters 4-27, inclusive. These filters cover the fundamental frequency range from 32 to 2000 c.p.s. approximately. Another two or three octaves of filters would be needed to fill out the upper portion of the entire audio-frequency spectrum. The transmission characteristics of these filters need not be perfect, from a frequency-range division standpoint. For example, a 10 db discrimination against frequencies in the adjacent pass-band is quite satisfactory for the purpose of this invention, although 20 db would be desirable. The outputs of filters 4-27 are combined through isolating networks (not shown) into four octavely related groups. II, III, IV, V, which are separately amplified by recorder amplified by recorder amplifiers 28-31. The outputs of the recorder amplifiers, together with appropriate signals for biasing the recording medium, are supplied individually to a four-channel head 32, recording on tape 33, and comprising individual recording elements 32a, b, c and d.

In greater detail, the filters 4-27 inclusive are each arranged to pass a frequency span of three semitones of the musical scale. So, filter 4 passes the fundamental of tones A6, A#6, B6, and nearby partials in the 6th octave of tones in lower octaves, while adjacent filter 5 passes only F#6, G6, G#6, filter 6 passes D#6, E6, F6 and 7

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passes C6, C#6 and D6. The four filters 4-7 encompass the entire 6th octave. The four filters 4-7 lead, respectively, to recorder elements 32a, b, c, d.

In essence, all the octaves follow the rule for the sixth octave, so that, for example recorder element 32a records only partials corresponding to A, A#, B, in all of the octaves.

In playback, FIGURE 2, the tape 33 moves past four-channel playback head 34, and the four playback signals (octaphonic channels II-V) are amplified separately by playback amplifiers 35-38 and radiated from separate loudspeakers 39-42. This system provides maximum economy for the purchaser of playback equipment, because the frequency-range division occurs in the recording part of the system. Only the recording studios require the filter set, and the users of the tapes and the playback systems gain the advantages.

The quality of music recordings varies greatly in accordance with the care employed and the equipment used in making the recording. However, a recorded track which is relatively free of intermodulation distortion can be badly degraded by the reproducing system. This is particularly true when the reproduction is at high sound level, or when a very large auditorium or arena must be filled by the sound reproduction. FIGURE 3 illustrates how octaphonic frequency-range division can be advantageously accomplished in reproducing from a single-channel recording of music. The system can, of course, be duplicated for stereophonic reproduction. Single-channel playback head 43 responds to the single track recorded on tape 44, and preamplifier 45 provides the full-range of the musical spectrum through common input 46 to the inputs of the filters 47-74. In this case the quarter-octave filters 47-74 separate the reproduced signal into quarter-octave bands which are octavely combined (through isolation means not shown) in mixing circuits II-V. Again, as in FIGURE 1, the four octaphonic channels are amplified and radiated by amplifiers 75-78 and loudspeakers 79-82. Although it is less economical for the filter set to be in the reproducing system, there is one great advantage. Such a reproducing system can accept program material from any recorded track. There is no problem of compatibility with the original recording system. However the octaphonic reproducing system cannot correct for non-linear distortions in the recording.

TABLE I.—QUARTER-OCTAVE IDENTIFICATION OF THE PARTIALS OF A COMPLEX THIRTY-HARMONIC TONE C₁

Group	II	C,	C#,	D
III	D#,	E,	F	
IV	F#,	G,	G#	
V	A,	A#,	B	
1	32.7	II	C ₁	
2	65.4	II	C ₂	
3	98.1	IV	G ₂	
4	130.8	II	C ₃	
5	163.5	III	E ₃	
6	196.2	IV	G ₃	
7	228.9	V	A ₃ +	
8	261.6	II	C ₄	
9	294.3	II	D ₄ +	
10	327.0	III	E ₄	
11	359.7	IV	F ₄ F# ₄	
12	392.4	IV	G ₄	
13	425.1	V	G# ₄ +	
14	457.8	V	A ₄ -	
15	480.5	V	B ₄ -	
16	523.2	II	C ₅	
17	555.9	II	C# ₅ +	
18	588.6	II	D ₅ +	
19	621.3	III	D# ₅ -	
20	654.0	III	E ₅ -	
21	686.7	III	F ₅	
22	719.4	IV	F ₅ F# ₅	
23	752.1	IV	F# ₅ -	
24	784.8	IV	G ₅	
25	817.5	IV	G# ₅ -	
26	850.2	IV	G# ₅ A ₅	
27	882.9	V	A ₅	
28	915.6	V	A# ₅	
29	948.3	V	A# ₅ +	
30	961.0	V	A# ₅ B ₅	

TABLE 2.—QUARTER-OCTAVE GROUPING OF THE PARTIALS OF ANY C TONE

II	IV	III	V
1			
2			
	3		
4			
	6	5	
8			7
9			
	11	10	
	12		
	13		
			14
16	22	19	15
17	23	20	27
18	24	21	28
	25		29
	26		30

TABLE 3.—QUARTER-OCTAVE IDENTIFICATION OF THE PARTIALS OF A COMPLEX TWENTY-HARMONIC TONE G₁

Group	II	C ₁	C ₂ #	D
	III	D ₁ #	E	F
	IV	F ₁ #	G	G ₁ #
	V	A	A ₁ #	B

1	49.0	G ₁	IV
2	98.0	G ₂	IV
3	147.0	D ₃	II
4	196.0	G ₃	IV
5	245.0	B ₃ -	V
6	294.0	D ₄ +	II
7	343.0	F ₄ -	III
8	392.0	G ₄	IV
9	441.0	A ₄	V
10	490.0	B ₄ -	V
11	539.0	C ₅ C ₅ #	II
12	588.0	D ₅	II
13	637.0	D ₅ #E ₅	III
14	686.0	F ₅ -	III
15	735.0	F ₅ #	IV
16	784.0	G ₅	IV
17	833.0	G ₅ #	IV
18	882.0	A ₅	V
19	931.0	A ₅ #	V
20	980.0	B ₅ -	V

TABLE 4.—QUARTER-OCTAVE GROUPING OF THE PARTIALS OF ANY G TONE

II	IV	III	V
	1		
	2		
3	4		
			5
6			
	8	7	
			9
11			10
12			
		13	
		14	
	15		
	16		
	17		
			18
			19
			20

It should be pointed out clearly that the octaphonic filter system does not direct all of the partials of a complex tone into a single channel, only those which are approximately octavely related. Table 1 shows as example of the routing of the individual partials of a highly complex musical tone having a fundamental frequency of 32.7 c.p.s. (C₁) and 30 harmonic partials. In the first column is the harmonic number. The second column is the frequency in c.p.s. The fourth column identifies the note nearest to the harmonic in the musical scale. (Plus and minus signs show the direction of deviation when coincidence is poor, and when the partial lies nearly half-

way both note letters are shown.) The third column shows which of the four octaphonic channels will transmit the harmonic. Table 2 brings the various harmonics together into four octaphonic channels. The number of harmonics in each channel varies from 5 to 10. In this example the II channel, which transmits the fundamental frequency, carries five of the first ten harmonics. Channels III and IV each carry two, and V has only one of the first ten. The next three harmonics go to channel IV. Although the lower harmonics are usually of greater amplitude than the higher harmonics, there are some complex tones in which the higher harmonics are significant. For this reason there is some advantage in locating the output of channel IV adjacent to II. These two channels carry ten of the first 13 harmonics, and 13 of the first 18 harmonics. This is why channels III and IV are transposed in FIGURES 1 and 2, and frequently throughout this application.

Another example will illustrate that it is also advantageous to have channel II nearby when the fundamental frequency lies in channel IV. Table 3 shows a 20-harmonic tone of fundamental frequency 49 c.p.s. (G₁), lying in channel IV. Table 4 groups the harmonics into octaphonic channels. It is apparent that channel II has the same relationship to a tone having its fundamental in channel IV as IV did to II in the previous example. The small differences in the high harmonics are because G₁ is in the middle of its quarter-octave filter range while C₁ is off center. The effects of harmonic distribution among the four channels upon tonal localization will be analyzed hereinafter in connection with FIGURE 11.

FIGURE 4 is a simplification of FIGURE 3, which takes advantage of the normal energy distribution in musical sounds, and of the relative inaudibility of the very low-frequency difference tones generated by combinations of signals in the lowest octaves of the musical scale. Tonal partials lying above C₃ (approximately 4000 c.p.s.) are generally quite weak, and can be omitted from the octaphonic filter system without much degradation in performance. The lower harmonics of the lower notes are sparsely distributed along the frequency scale in most music. Furthermore they are not easily localized by listeners and their difference tones are hardly audible. Therefore they can be combined as shown in FIGURE 4, with small degradation in purity of reproduction. High-pass filter 83 and low-pass filter 84 can be connected to amplifiers and loudspeakers designed specifically for their frequency ranges or, for the sake of economy, can be combined and mixed into all four of the octaphonic channels. Preferably the loudspeakers in this case would be "woofer-tweeter" combinations with dividing networks, in order to avoid intermodulation distortion between widely separated frequencies.

An alternative means for separating the tonal components into octaphonic channels is the use of multi-resonant filters. An example is a bank of suitably damped flexible, vibrating strings tuned to the twelve equally tempered frequencies in a low octave of the scale. In FIGURE 5 such a set of string filters 84-95 is shown schematically, with separate input transducers 96-107 and output transducers 108-119. The electro-mechanical transducer usage could be simplified. A single input transducer T of high mechanical impedance could drive all twelve strings, and each group of three strings could have a common output transducer, leading to channel amplifiers 75-78 and the corresponding loudspeakers 79-82. This system has the advantage that any given amplification channel will transmit all of the harmonics of a tone lying in its group designation. However some of the higher harmonics will also be reproduced in other channels as well, so it will be necessary to attenuate the high-frequency response of all channels to compensate for the multiple reproduction of the higher frequencies. The chief advantage of this system is that only twelve filters are required, and they are of a type which can be

sharply tuned at each resonance frequency at relatively low cost.

The simplest application of the octaphonic principle to musical instruments is to instruments which generate each individual musical wave form separately. The pipe organ is an example. If a small pipe organ were to be amplified so as to fill a large arena, it would be advantageous for an intermodulation distortion standpoint to have all of the C, C#, D pipes so arranged as to be picked up by one microphone; all of the D#, E, and F pipes by another microphone; and so forth. Each microphone would be connected to its own amplifier and loud-speaker system.

The counterpart for the various electrical and electronic waveform-generating types of instruments is shown in FIGURE 6. Generators in bank 120, keyed on from the organ clavier, may be any type of complete waveform generator, such as an electronic generator of a complex tone spectrum, an electrostatic scanner of a variable capacitance generator, a magnetic scanner of a specially distributed or recorded magnetic waveform, a photoelectric pickup of a photographic image of a musical waveform, and the like. In all of these the outputs from all of the C's, C#'s, and D's in each octave of each stop would be combined (with reasonable care in isolation and loading) and amplified in amplifiers A and radiated separately from the other three groups of tones, in radiators R. Note in FIGURE 6 that the loudspeakers have acoustically separate back spaces because they are mounted close together. Preferably the loudspeakers would be spaced apart as well as partially enclosed so that intermodulation distortion resulting from acoustical coupling between loudspeakers will be minimized.

Although the explanation of this form of octaphonic system for organs is simple and straightforward, this form of the system has the disadvantage that each individual tone has less spatial spread than in some of the later systems (e.g. FIGURE 9). Patent No. 2,596,258 separates the tones of the scale into two groups for separate amplification and radiation, with alternate notes in the equally tempered scale going to different channels. The purpose of that invention was to prevent electrical beating effects between tones having equally tempered intervals of a perfect 4th or a perfect 5th (e.g. C-F and C-G). The present invention differs from Patent No. 2,596,258 in that the tones have a greater variety of source locations. Furthermore the musical possibilities for intermodulation distortion are negligible in comparison to Patent No. 2,596,258, in which a number of frequently used combinations of tones (e.g. major third, augmented fifth) are amplified and radiated together with attendant intermodulation distortion.

A simplification of the system of FIGURE 6 is shown in FIGURE 7. Here all the lower tones in the scale are combined and supplied to amplifier 121 and loudspeaker 122, specifically designed for low tones. In this range of playing the simultaneous tones are usually (although not always) octavely related anyway, in contrast to the upper octaves where chords are common.

In the system of FIGURE 7, the octaphonic division of tones is followed for all tones above the "lower tones," the division point being relatively arbitrary. The amplifiers and radiators are accordingly denoted A and R, as in FIGURE 6.

In the formant type of electronic musical instrument complex waveforms are selected from a musical scale of generators (either keyed-on or keyed-output, the latter being indicated in FIGURE 8) and are supplied in combination to common stop (or tone-color) circuits prior to amplification. In other words the same electrical wave-shaping network is used regardless of fundamental frequency. This method of producing tone colors offers wide variety of timbre at relatively low cost, because the tone color filters do not have to be reproduced for each note or each octave. For the advantages of the octaphonic

principle to be realized in the formant type of instrument it is necessary only to wire each octave of tone outputs in four groups, and to combine them octavely in mixing circuits as shown in FIGURE 7. Each octaphonic channel of signals is passed through an individual stop filter before separate amplification. Connections from coupled scales of generators or key switches are made in the usual manner. Each stop (Y, for example) would employ four similar (but not necessarily identical) tone color filters Y_1, Y_2, Y_3, Y_4, Y_5 each receiving a different quarter of every octave. Stops X, W, U, and V would also have 4 filters each. Stop switches, whether on the input or the output of the filters, would be of the 4-pole type. Thus the octaphonic principle can be applied to the formant instrument simply by quadrupling the least expensive part of the electronic system, the tone color filters.

Resonator organs of the type described in application for U.S. Patent Ser. No. 46,704, filed in the name of Wayne, are ideally suited to the octaphonic principle, because the organ already contains (for other purposes) an ideal set of filters for octaphonic use. Two notes of such an organ are shown in FIGURE 9. Organ generator C_1 supplies all the necessary harmonics of a complex wave to common input point 124. Generator G_1 does the same for common input 125. From these two common input points are connected many resistors 126a, b, c, etc., and 127a, b, c, etc. which determine the amount of signal current supplied to the appropriate singly resonant circuits (or resonators) in circuit bank 128. The circuits selected from this bank are resonant at or near harmonic frequencies of the input tone waves. Thus the resistors 126a, b, c, etc. are spectrum shaping resistors for the note C_1 . Different stops have different spectrum shaping resistor values for the same fundamental frequency. Only one stop is shown here for simplicity. However, no matter how many input circuits are connected to the resonator bank 128, the outputs of the individual resonators are connected octaphonically in groups II-V, and amplified and radiated separately for minimum intermodulation distortion.

Referring now to the second object of the invention, assume that each loudspeaker R in FIGURE 9 has been designed to have the best possible directional characteristic throughout its frequency range. The multiplicity of channels, and the fact that no note is played on more than one loudspeaker, allow the angular distribution of energy from the system to be just as uniform as one loudspeaker can provide. Each loudspeaker is radiating a different set of frequencies, and can be driven beyond the usual limitations due to non-linearity before audibly spurious frequencies are generated. The necessity to combine loudspeaker outputs in "beaming" arrays is obviated. When higher powers are required, the number of octaphonic channels can be increased to six or even twelve before any one channel duplicates the frequency of another.

FIGURE 10 is a simplification of FIGURE 9, in which all of the lower partials, irrespective of location within the octave, are combined for separate amplification by amplifier 121 and radiation by special low-frequency loudspeaker 122. This simplification reduces the number of very low-frequency loudspeaker units required. Such units are usually large and require large enclosures, so reduction of their number minimizes space requirements and cost. This simplification is possible because chords are seldom played in the pedal section of the organ (except by virtuosos), and the difference tones generated by such low-frequency partials are too low in frequency to be audible.

The harmonic-synthesis type of electronic organ in FIGURE 11 uses a bank 123 of continuous sine-wave generators which are tuned to the equally tempered scale. The generator outputs are wired to ganged key-switches which provide simultaneous switching of a number of approximately harmonically related frequencies, eight in the case of FIGURE 11. Because of the complexity in

wiring of such a system, only three ganged key-switches are shown for the simple case of a major triad, C₂, E₂, G₂. The principal commercial type of harmonic synthesis organ employs harmonic drawbars. All of the first harmonics are normally collected and supplied to drawbar No. 1, all of the second harmonics to drawbar No. 2, and so forth. FIGURE 11 shows how the octaphonic principle can be applied to a harmonic synthesis organ, by using four sets of drawbars which (for convenience to the player) would be ganged, so that a single motion would be required for setting the relative amplitude of each harmonic, just as in present harmonic synthesis organs. Note that for C₂ the output of the first harmonic switch goes to the first drawbar of the lowest set, and the output of the second harmonic switch goes to the second harmonic drawbar of the same set. However the output of the third harmonic switch goes to the third drawbar of the next higher set. 4th harmonic, being octavely related, goes to the lowest set of drawbars, but the 5th harmonic goes to the 5th drawbar in the third set. The seventh harmonic of C₂ (frequently omitted in synthesis organs because the nearest equally tempered tone is grossly in-harmonic) would be routed to the 7th drawbar of the top set. Similar connections are shown for E₂ and G₂. This enables the partials of a harmonic synthesis organ to be amplified and radiated octaphonically with audible intermodulation distortion practically eliminated.

In the electronic organ field there is an entire class of modulating devices and circuits which make the electronically produced tone more interesting, more realistic, or more desirable aesthetically to the listener. Examples are phase vibrato circuits, chorus or celeste circuits, reverbation circuits or systems, and random or non-periodic modulators. It has frequently been found desirable to modulate differently in different octaves, as in Wayne Patent No. 3,004,460, and to radiate the different modulations separately from each other and from the original unmodulated signal, as in Wayne application Ser. No. 45,609. The octaphonic principle of frequency-range division provides advantages over previous systems employing modulations in that the different (or uncorrelated but similar) modulation effects are applied to different frequencies within the same octave. FIGURE 12 is an example in which, in addition, each individual complex tone will have space modulation within itself. This is because some of the harmonics are being modulated differently from the basic group of harmonics which are approximately octavely related. In FIGURE 12 the bank of singly resonant circuits 128 of previous FIGURES 9 and 10 is the source of signals to be combined octaphonically. The scale of generators 120 in FIGURE 6, or the scale of key switches 123 of FIGURE 8, could just as easily have been used. Had they been, however, only the first advantage, i.e. different or uncorrelated modulation of different notes within the same octave, would have been achieved. In the case of the resonator organ the second advantage of modulation enhancement within the partial structure of a single tone is also achieved.

Assume for discussion that the channel modulators in FIGURE 12 are phase shift circuits 129-132, and that the channel modulators are under the control of suitably filtered sources 133-136 of random noise. These could, of course, be different bands of noise from a single noise source for simplicity and economy. The important thing is for the modulations to be independent or uncorrelated. If a triad C, E, G, of pure flute tones is played, in which only the first harmonic partial is of audible amplitude, the corresponding tones will be radiated by loudspeakers 79, 81, and 80 respectively. The phase modulations of each tone will be independent in magnitude and time. At any instant any pair of tones may have phase shifts which are even opposite in direction. When these phase shifts are reflected into the acoustical standing wave system of the listening room, it will sound to the listener as if the three tones in the triad are quite independent

of each other. When more complex tones (such as diapason, string, or reed types) emerge from the resonator bank 128, a majority of the energy of any given tone will generally go to one channel. However smaller parts of the energy of the same tone will be routed to other channels (refer to Table 4), and will therefore be modulated somewhat differently. Thus for complex tones the independent modulation of sub-groups of partials, combined with the radiation of these partials from spaced loudspeakers, gives each individual complex tone an apparent location which is variable in time and space about the normal location which would be observed if the modulations were turned off. This adds greatly to the "liveness" of the musical tone heard by the listener. Moderate amounts of modulation make the tone resemble pipe organ tone. Greater modulation gives a novel, musically interesting effect.

When the complete audio-frequency spectrum, such as the output of a single division of an electronic organ, is radiated octaphonically, the apparent location of the individual tones will depend upon (a) the number of octaphonic channels (four, six, or twelve), (b) the type of electronic organ (waveform) generator, formant, resonator, harmonic synthesis), and (if the organ is a resonator type) (c) the degree of complexity of the tone spectrum radiated. The listener's ability to localize sounds coming from each of the channel loudspeakers will depend upon the angular spread of the loudspeakers, as seen by the listener, and upon the acoustics of the listening space.

For the waveform generating and formant types of organ, all of the harmonics of a given fundamental frequency will be radiated by the same loudspeaker system. Consequently the listener will localize the tonal sources more definitely than he would when listening to the octaphonic output of a resonator organ, for which the motion effects of one organ division are shown in FIGURE 13. Each square in the diagram represents the location of a channel loudspeaker identified by the channel number underneath. No vertical motion is intended to be implied by the four horizontal bands within each square. This is simply a convenience for showing what the situation is with regard to each of the four note-groups in a four-channel octaphonic system. Table 4 has previously shown how the harmonics are distributed among the four output channels for a complex tone having twenty harmonics. If only the fundamental has an audibly appreciable amplitude, the listening situation is the same as for waveform generating or formant types of organs. Each tone will come from the particular loudspeaker associated with its note-group. At the other extreme are tones having many prominent harmonics. Seldom is the spectrum so highly developed as a saw-tooth tone wave, in which the spectrum level has a negative slope of six db per octave. More stringent tones than the saw-tooth wave tend to be musically unpleasant, and the unfiltered saw-tooth itself borders upon this condition. In FIGURE 13 the saw-tooth wave has been assumed as a kind of upper limit on the distribution of energy into the higher harmonics for calculating a center of gravity for the power distributed within a highly complex tone wave, taking into account the harmonic distribution shown in Table 4. For notes in Groups III and IV 84% of the power radiates from the loudspeaker of the same designation. Ten percent of the power radiates from the adjacent end loudspeaker, and four percent from the other end loudspeaker, with a mere two percent from the fourth loudspeaker. Although the spectral energy is somewhat spread, the center of gravity is squarely in the center of the appropriate loudspeaker. The situation is slightly different for channels II and V. Here there are no loudspeakers on one side to provide a balancing contribution. Consequently the centers of gravity for a highly complex tone lie slightly inside the actual loudspeaker locations. For less complex tones, in general, the center of gravity will lie between the center of the end loudspeakers and

the dots shown for the saw-tooth spectrum case. One can easily design a bizarre tonal spectrum, with the aid of Table 4, which will make a Group II tone come from the Group IV loudspeaker, but such rough spectra are not common. In any case the octaphonic system will provide motion effects within a single organ division, and this is what is desired rather than strict identification of a particular note with a particular location.

The calculations on energy center of gravity are not intended to imply that a listener will localize the sounds strictly on a basis of energy centroid. The ability of listeners to localize sound distributed in space, and especially the mechanisms by which this is accomplished, are still not fully understood. However the difference between an octaphonic tone radiation system and a four-parallel-channel tone radiation system (in which all of the tones are radiated equally from all of the loudspeakers) can easily be heard and demonstrated. In the octaphonic system musical definition is greatly enhanced, and the sounds are more interesting, even to the musically naive observer. This advantage is in addition to the freedom from intermodulation distortion, and the freedom from the undesirable effects of arrays of multiple loudspeakers radiating the same sounds.

FIGURE 14 is an example of the use of the octaphonic principle in a multi-manual electronic organ. It shows an advantageous distribution of the loudspeakers in a three-manual organ consisting of Great, Swell, and Choir divisions. The Pedal division has been omitted from the discussion, but it could be combined with the Great division, or it could have its own widely distributed loudspeakers. The purpose here is to make the Great division sound large in comparison to the Choir division, with the Swell division intermediate in apparent size. The dashed lines enclose the Choir division and the Swell division. The horizontal spread is much greater in the Swell division than in the Choir division. A vertical spread has also been provided for the Great division by duplicating its loudspeakers at a lower altitude. However an even better arrangement than the one shown in FIGURE 14 would have the Great division divided into six or twelve octaphonic channels, and spread over the same area shown in FIGURE 14. This would conserve the advantage in directional characteristics while enlarging the Great division's apparent size. Note that the group numbers have the reverse numerical order, left to right, in the Great division. This balances one division against the others when the full organ is played, utilizing the full solid angle available, no matter what chords or progressions are most probable in the key of the musical selection being played.

Many other refinements and extensions of the invention, within the scope thereof, will occur to those skilled in the art. It is intended therefore that the scope of the present invention not be limited by the foregoing disclosure, but rather by the appended claims.

What I claim is:

1. In a music system, a source of electrical signals representing musical tones and having at least fundamentals distributed over at least two octaves, means for dividing said tones into not less than three nor more than six channels each collecting only tones of adjacent nomenclature, and means for separately transducing the combined tones.

2. In a music system, a source of electrical signals representing musical tones and having a multiple octave gamut of frequencies corresponding with the musical scale, means for separating groups of frequencies included in at least two but not more than four musically adjacent semitones of each octave, means for combining those of said groups having at least approximately only octavely related frequencies, and means for separately transducing each of the combined groups.

3. The combination according to claim 2 wherein said source is an electronic organ of the type employing complex tone sources and tone color filters, wherein is

provided a separate tone color filter for each of said groups of tones of each of said octaves.

4. The combination according to claim 2 wherein said source is an electronic organ employing singly resonant circuits for separating out frequencies of complex tone sources, and wherein said means for separating comprises said circuits.

5. In an electronic organ, a gamut of complex tone generators arranged in frequency according to at least a substantial portion of the musical scale, single frequency resonators responsive to all said tone generators for separating out individual partials, means for combining said individual partials of each octave in groups of adjacent frequencies, at least a major part of said groups encompassing no more than four frequencies, means for combining only groups including at least some octave related partials, and means for separately transducing the combined groups.

6. In a music system, a source of complex tones covering at least a portion of the gamut of musical tones, means for separating out of said tones within each octave groups of partials which are adjacent in frequency, each group spanning at least two adjacent half tones but no more than one quarter of an octave, means for combining only those groups including octavely related frequencies, and means for separately transducing each of the combined groups.

7. The combination according to claim 6 wherein the means for transducing are acoustic radiators, said acoustic radiators being spatially relatively widely separated with at least some radiators of frequency adjacent groups being separated by at least one other radiator.

8. The combination according to claim 6 wherein, for a system wherein each group comprises three adjacent fundamentals and partials, said radiators are spatially arranged in the order two, four, three, five, where the order of the frequencies is two, three, four, five.

9. The combination according to claim 6 wherein said source is a multi-division organ, wherein analogous groups of frequencies are separately derived for separate divisions of said organ, wherein said transducers are acoustic radiators, a different one for each group of each of the separate divisions, and wherein at least certain of the separate radiators are arranged to be spatially non-adjacent if frequency-wise adjacent.

10. The combination according to claim 6 wherein said radiators are arranged to provide approximately amplitude balanced outputs for all directions as seen from a point spatially balanced with respect to said radiators.

11. In a music system, a source of complex tones covering at least a portion of the gamut of musical tones, means for separating out of said tones within each octave groups of partials which are adjacent in frequency, each group spanning at least two but no more than one quarter of an octave, means for combining only those groups including octavely related frequencies into combined groups, and means for separately transducing each of the combined groups wherein is provided means for differently modulating each of the last named groups.

12. In a music system, a source of electrical signals representing musical tones and having a gamut of frequencies corresponding with the partials of the musical scale, means for separating groups of partials including at least two musically adjacent partials from said gamut, each group scanning no more than four adjacent fundamental frequencies of each octave, means for combining groups having at least approximately only octavely related frequencies, means for separately transducing each of the combined groups, wherein said source is an electronic organ employing singly resonant circuits for separating out frequencies of complex tone sources, and wherein said means for separating comprises said circuits, and wherein is provided means for differently modulating each of the combined groups.

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13. In an organ system, a plurality of continuous generators of sine waves having frequencies appropriate to partials of the musical scale for a plurality of octaves, means for combining in separate channels selected ones of said sine waves appropriate to notes of complex tones of not less than two nor more than four adjacent nomenclatures for all said octaves, and means for separately transducing the contents of said separate channels.

14. In a music system, an electric organ including a plurality of keyed on generators of complex musical waveforms each representing a note of a musical multi-octave gamut of notes,

four channels each terminating in an electro-acoustic transducer, and

means for collecting into each of said channels only those of said waveforms which represent three adjacent semi-tones taken from said octaves such that each of said channels carries only notes of nomenclature not represented in any other of said channels.

15. In a music system, an electrical organ including a plurality of keyed on generators of complex musical

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waveforms each representing a note of a musical multi-octave gamut of notes, at least three channels each terminating in an electro-acoustic transducer,

means for collecting into each of said channels only those of said waveforms which represent plural adjacent semi-tones taken from said octaves such that each of said channels carries only notes of nomenclature not represented in any other of said channels.

References Cited

UNITED STATES PATENTS

2,596,258	5/1952	Leslie	-----	84-1.17
2,830,481	4/1958	Hanert	-----	84-1.01
3,041,910	7/1962	Leslie	-----	84-1.11
3,215,767	11/1965	Martin	-----	84-1.24
3,235,649	2/1966	Leslie	-----	84-1.11

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