

Oct. 17, 1961

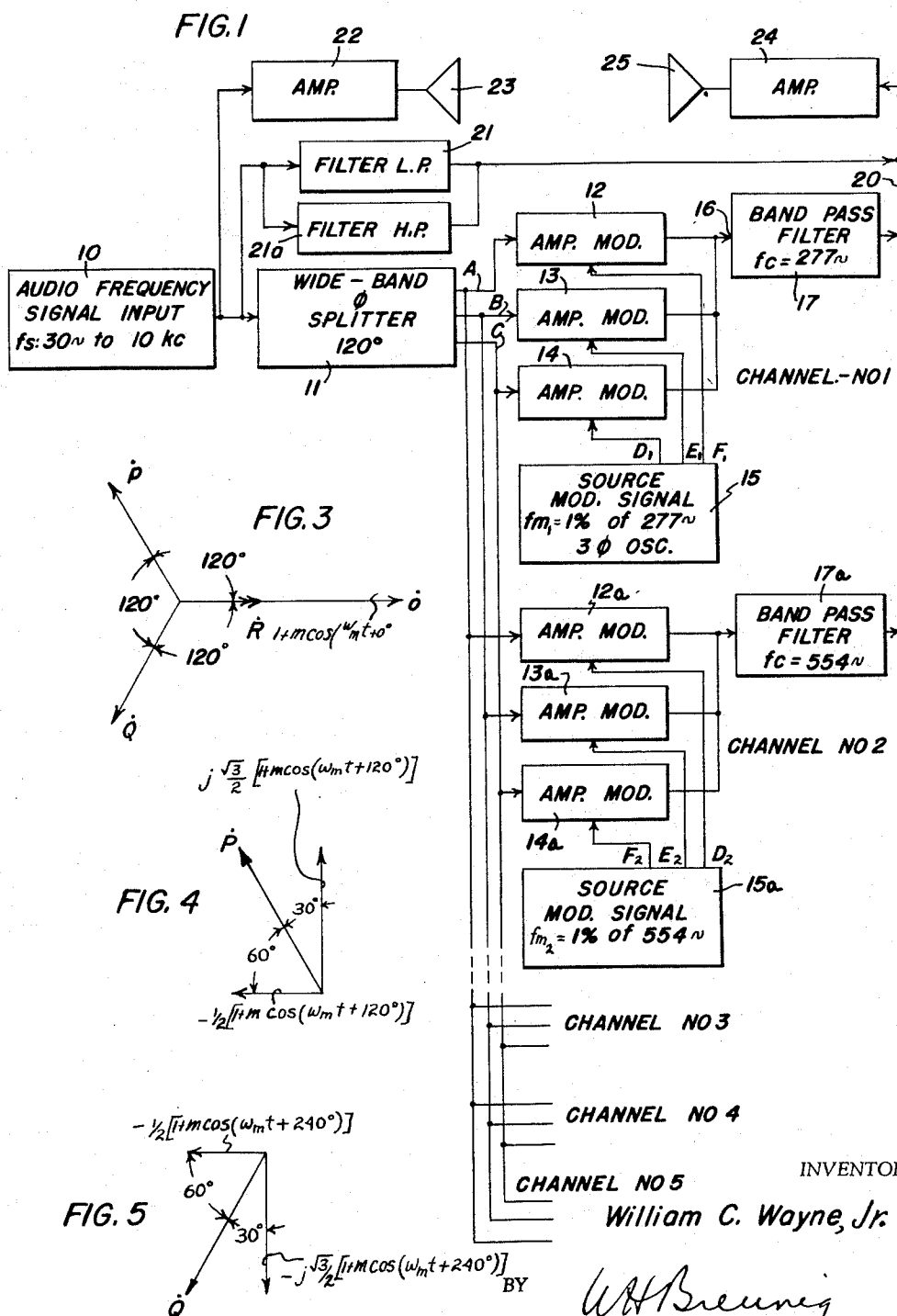
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3,004,460

AUDIO MODULATION SYSTEM

Filed Dec. 31, 1956

2 Sheets-Sheet 1.



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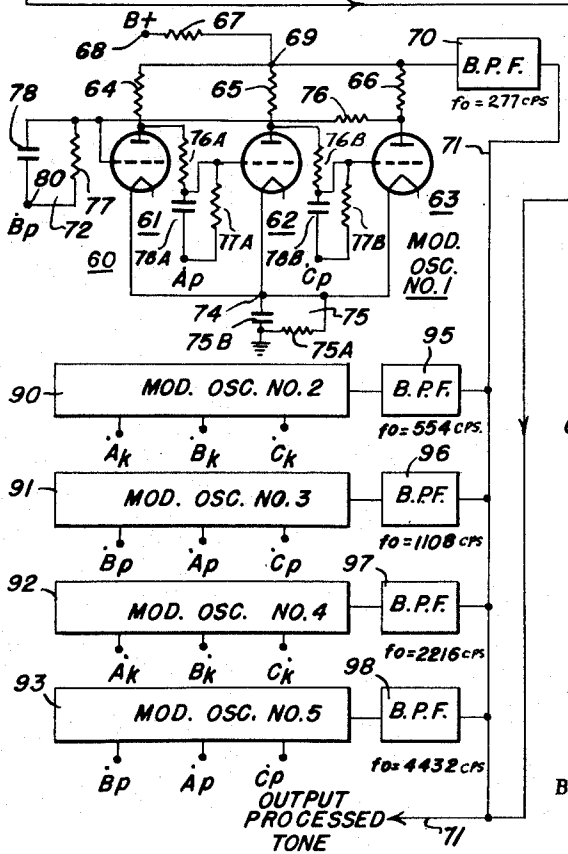
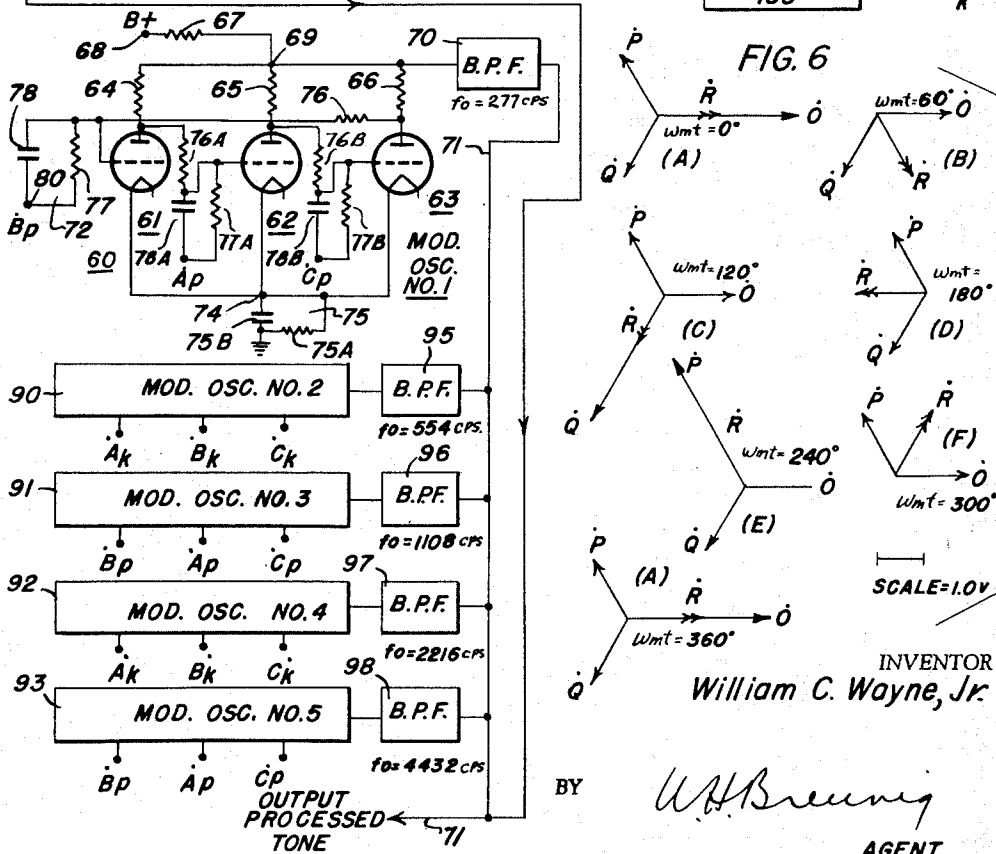
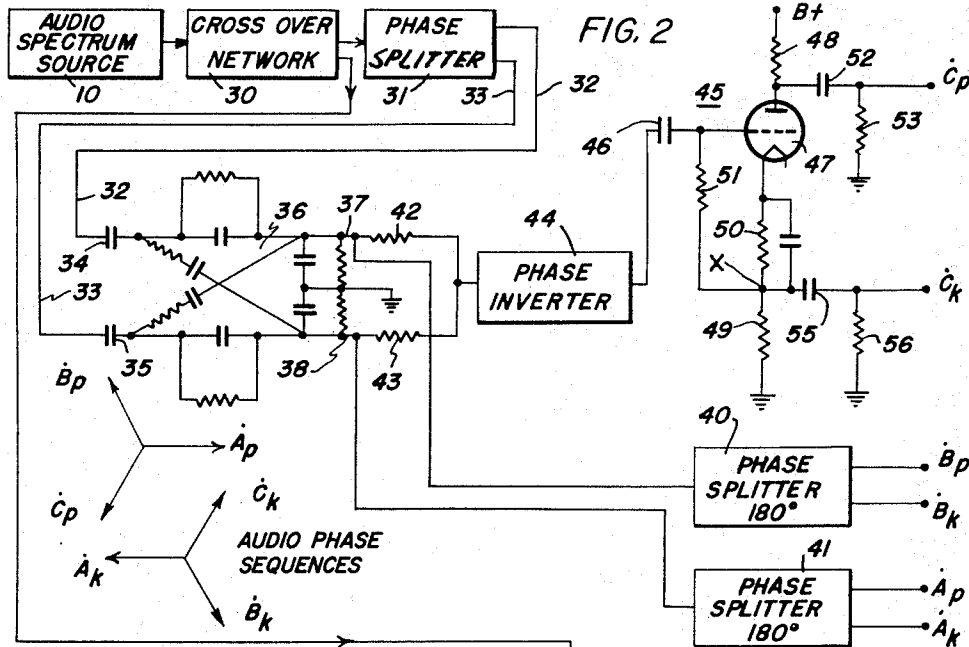
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2 Sheets-Sheet 2



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3,004,460

AUDIO MODULATION SYSTEM

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46 Claims. (Cl. 84-1.01)

The present invention relates generally to systems for achieving an ensemble effect in music by processing a band of audio frequencies, and more particularly by translating the frequency spectrum so that it is either sharp or flat in controllable degree, over its entire extent, or is in part flat and in part sharp. The translated frequency spectrum may be combined with a corresponding untranslated frequency spectrum acoustically, as by transducing the translated and untranslated spectra in, preferably space separated, loud-speaker systems.

The traditional pipe organ consists of many ranks of pipes which are invariably somewhat out of tune. Certain ranks of pipes, referred to as "celestes," are purposely detuned by a considerable amount to produce a rich ensemble effect in the composite tone, which is especially desirable for use in ecclesiastical music.

It is a primary object of the present invention to provide a system for electrically processing a musical frequency spectrum, from whatever source derived, so as to achieve a processed frequency spectrum which is capable of simulating the ensemble effect of pipe organs, and more particularly the celeste effect, and which is, in fact, more flexible in respect to the variety of ensemble effects made available than is the traditional pipe organ.

Briefly describing the present invention, as related to a specific embodiment thereof, a plurality of wide-band, single side-band modulators is employed, each of which continuously shifts the phase of a wide-band audio spectrum in such sense as to introduce a continuously changing phase shift of the entire spectrum in a given direction, which is equivalent to a frequency shift of the entire spectrum in a given sense, i.e., either flat or sharp. Different octaves of the wide-band spectrum are selected from the wide-band outputs of the several modulators by means of band-pass filters, and the filtered sub-bands are then recombined to provide a processed wide-band frequency spectrum. The latter may be thus translated in frequency over its entire range either flat, or sharp, and in controllable extent, or certain octaves may be translated flat and certain others sharp, if desired.

The processed and unprocessed tones may be acoustically transduced by a single transducer, or by adjacent transducers. Alternatively, the unprocessed frequency spectrum may be fed to one loud-speaker system, and the processed frequency spectrum to a second loud-speaker system widely spaced from the first, in order to achieve maximum spatial effect. This effect is especially appreciated when heard binaurally and corresponds to an apparent tonal movement, thus greatly enhancing the musical interest of the program material.

The modulating system contains no mechanically moving parts, but is all-electronic. It may be inserted in any electrical signal line containing program material to process the program material, whether the latter is derived from an electronic organ, a single manual, or a single stop, a moving picture sound track, a phonograph reproducer, a microphone, or the like.

More specifically describing a modulator, according to the invention, from a wide band audio spectrum are derived, by phase splitting, three components of identical frequency content and identical amplitudes, corresponding frequencies of which are displaced 120° in time phase. The phase-split components of the original signal are next

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amplitude modulated at a low frequency rate, each in response to one phase of a three phase subaudible frequency oscillator, in such manner that upon linear recombination of the amplitude modulated signals a processed signal is obtained whose phase angle is continuously changed in a given sense relative to the input as a fixed reference value. By selecting the phase sequence of the low frequency oscillator outputs to be opposite to the phase sequence of the phased audio bands, the processed output will have a continuously varying phase shift in a positive or increasing sense, with a consequent increase in frequency. By reversing the relative phase sequences, the phase shift is in the opposite sense, i.e., the processed output will be "flat," or lower in frequency relative to the original input band.

If it is desired to maintain the frequency shift corresponding with any continuous phase variation at a selected constant percentage value, frequency shift of the entire audio band is accomplished in separate channels for separate sub-bands of the audio spectrum, and the modulation frequency selected for each channel is a fixed percentage of the center frequency of a desired sub-band. However, experience indicates that the selected percentage should decrease somewhat as the higher frequency sub-bands are approached to yield most pleasing musical results for widely varying input spectra encountered in practice.

Sub-bands are selected, from the several frequency shifted bands, which have the desired values of percentage frequency deviation, and the selected sub-bands are additively combined to re-form a processed audio frequency band.

Since the algebraic sign of the frequency shift, positive or negative, corresponds with the relative phase sequences adopted for the low frequency oscillator outputs and for the phase shifted spectra, in the modulation process, the sub-bands may have frequency deviations of either algebraic sign at will. It is preferred to derive sub-bands adjacent ones of which are frequency shifted in opposite sense. It is further preferred that the sub-bands shall be of octaval widths, rather than of equal widths, so that notes of corresponding nomenclature and adjacent in the musical scale shall be frequency shifted in opposite senses or directions. On a statistical basis the same effect occurs in respect to partials, and where applicable the term harmonic may be taken to include partials, and vice versa to avoid repetitious language. Partial is a component of tones which have frequencies that are not integral multiples of a fundamental frequency. They occur in piano and bell tones for example.

It is, accordingly, an object of the present invention to provide a system for shifting in frequency all the frequency components of an audio spectrum.

It is another object of the invention for providing a system for shifting the frequency of sub-bands of an audio spectrum positively or negatively, as desired, and in controllable extents.

It is still a further object of the present invention to provide a system for achieving an ensemble effect by converting components of an audio spectrum to relatively displaced frequency positions, and electro-acoustically transducing the original band and the converted band concurrently.

Still another object of the present invention resides in the provision of a system for processing an audio signal band representing music so that notes of the same nomenclature in adjacent octaves are frequency shifted in opposite senses.

It is a further object of the present invention to provide a system for shifting the frequencies of a wide audio spectrum all with substantially the same percentage deviation, by deriving from the wide audio spectrum duplicate wide audio spectra which are symmetrically phase dis-

placed, one from the other, and amplitude modulating the separate phases in response to a modulating signal in such relative phase as to cause the phase of the the phasor sum of the symmetrically phase displaced spectra to rotate continuously in a given direction without amplitude variation.

It is still another object of the present invention to provide a novel and particularly economical system for frequency shifting a spectrum by amplitude modulating phase displaced duplicates of the spectrum, in response to a modulating signal, by utilizing a ring oscillator as a source of modulating signal and also as an amplitude modulator.

Still a further object of the present invention resides in the provision of a combined modulator-oscillator in the configuration of a ring having one unilateral conducting device per stage, in which each device performs its function as part of the oscillator and also perform as an amplitude modulator.

It is a further object of the invention to provide a system for frequency shifting a wide band of frequencies with substantially constant percentage deviation, by generating a duplicate of the band of frequencies, phases of the separate frequencies of which are continuously phase rotating in a given sense at different but constant velocities, abstracting from the latter sub-bands of frequency having the required percentage deviations, and combining the sub-bands additively to provide the required frequency band.

A further object of the invention resides in the provision of a system for processing an audio signal band representing music in such manner that notes of the same nomenclature in adjacent octaves are frequency shifted in opposite senses but with at least approximately the same percentage frequency deviation.

The above and still further objects, features and advantages of the present invention will become apparent upon consideration of the following detailed description of one specific embodiment thereof, especially when taken in conjunction with the accompanying drawings, wherein:

FIGURE 1 is a block diagram of a system according to the invention;

FIGURE 2 is a circuit diagram, partially in block form, corresponding with certain elements of the system of FIGURE 1; and

FIGURES 3-6, inclusive, are phasor diagrams useful in explaining the system of FIGURES 1 and 2.

Referring now more specifically to FIGURE 1 of the accompanying drawings, the reference numeral 10 denotes a source of an audio frequency band or spectrum preferably representative of music, and may be an electronic organ, or one or more of the divisions thereof, or a single manual, or a single stop, a movie sound track, a disc or magnetic tape reproducer, or any other source available in the art.

The spectrum provided by the source 10 is processed in a system comprising a wide-band 120° phase splitter 11, which includes output leads A, B, C, on which appear the audio frequency spectrum f_s , or some portion thereof, all the frequencies of which have equal amplitudes, but are in the relative phases, for leads A, B, C of $f_s \angle 0^\circ$, $f_s \angle 120^\circ$, $f_s \angle 240^\circ$. To simplify the exposition the signal components appearing on leads A, B, C, respectively, will be denominated components $\dot{A} = A \angle 0^\circ$, $\dot{B} = B \angle 120^\circ$, and $\dot{C} = C \angle 240^\circ$.

The $\dot{A}$ component is applied to an amplitude modulator 12, the B component to an amplitude modulator 13, and the $\dot{C}$ component to an amplitude modulator 14. To the several amplitude modulators 12, 13 and 14 are applied signals from the separate phases of a three phase, sub-audio frequency oscillator 15. The outputs of the latter may be denominated $\dot{D}$, $\dot{E}$, $\dot{F}$, for convenience, the relative phases being, respectively, 0° , 120° and 240° , it being understood, however, that the relationship of the

phase components of the sub-audio frequency oscillator to the phase components of the audio band may be reversed, if desired, i.e., $\dot{A}$, $\dot{B}$, $\dot{C}$ may be modulated by $\dot{D}$, $\dot{E}$, $\dot{F}$, respectively, or by $\dot{F}$, $\dot{E}$, $\dot{D}$. It will become clear, as the exposition proceeds, that the relative positions of the two sets of phase angles determines the sense of phase variation of the system, and hence the direction of frequency shift. The amplitude modulated output audio signals, corresponding with the unmodulated signals $\dot{A}$, $\dot{B}$, and $\dot{C}$ are $\dot{O}$, $\dot{P}$ and $\dot{Q}$, respectively in what follows.

The outputs of the several amplitude modulators 12, 13 and 14 combine additively on lead 16, and a segment or sub-band of the audio spectrum is selected by means of a band-pass filter 17, which may pass one octave band to the final output lead 20. Accordingly, the band-pass filter 17 may have a center frequency, $f_c = 277$ c.p.s., so that, as far as the final output 20 is concerned, only the sub-band centered on 277 c.p.s. is modulated by source 15.

A mathematical analysis of the modulation process is provided as follows making reference to FIGURES 3, 4 and 5 to clarify and enable visualization of the analysis.

FIGURE 3 of the accompanying drawings is a phasor diagram in which are portrayed the three phase, audio frequency signals, having components $\dot{O}$, $\dot{P}$, $\dot{Q}$, in the phase sequence O, Q, P at one instant of time at which $w_m t = 0$. The modulation phase sequence is also assumed to be O, Q, P for this analysis.

The resultant output of the modulation system is

$$(1) \quad \dot{R} = \dot{O} + \dot{P} + \dot{Q}$$

where $\dot{R}$ is indicated on FIGURE 3 by a double arrow-head, and the dots indicate that the quantities are complex.

$$(2) \quad \dot{O} = E_1 [1 + m_1 \cos(w_m t + 0^\circ)] \cos(w_s t + 0^\circ)$$

$$(3) \quad \dot{P} = E_2 [1 + m_2 \cos(w_m t + 120^\circ)] \cos(w_s t + 120^\circ)$$

$$(4) \quad \dot{Q} = E_3 [1 + m_3 \cos(w_m t + 240^\circ)] \cos(w_s t + 240^\circ)$$

where w_m and w_s are the modulating and signal angular velocities, respectively and m_1 , m_2 and m_3 are the modulation indexes applicable to the several signals. Assuming equal per unit modulation indexes for all phases, $m_1 = m_2 = m_3 = m$.

We may view the rotating system of the $\dot{O}$, $\dot{P}$ and $\dot{Q}$ phasors at the angular velocity w_s , i.e., we may assume that we are rotating with the vector system at angular frequency w_s , and examine just the amplitude variations of the several phasors. The P phasor may be resolved into real and imaginary components (FIGURE 4) having the following values, assuming $E_1 = E_2 = E_3 = 1.0$ volt:

$$(5) \quad -\frac{1}{2} [1 + m \cos(w_m t + 120^\circ)]$$

$$(6) \quad +j \frac{\sqrt{3}}{2} [1 + m \cos(w_m t + 120^\circ)]$$

The Q phasor may likewise be resolved into components, having the following values

$$(7) \quad -\frac{1}{2} [1 + m \cos(w_m t + 240^\circ)]$$

$$(8) \quad -j \frac{\sqrt{3}}{2} [1 + m \cos(w_m t + 240^\circ)]$$

$$(9) \quad \text{Adding, } \dot{O} + \dot{P} + \dot{Q} = \dot{R}$$

Real parts of $\dot{R}$

$$(9) \quad 1 + m \cos(w_m t + 0^\circ) - \frac{1}{2} [1 + m \cos(w_m t + 120^\circ)] - \frac{1}{2} [1 + m \cos(w_m t + 240^\circ)]$$

Imaginary part of $\dot{R}$

$$(10) \quad +j \left[\frac{\sqrt{3}}{2} [1 + m \cos(w_m t + 120^\circ)] - \frac{\sqrt{3}}{2} [1 + m \cos(w_m t + 240^\circ)] \right]$$

Employing the identities

$$(11) \quad \cos(\alpha + 120^\circ) = -1/2 \cos \alpha - \frac{\sqrt{3}}{2} \sin \alpha$$

$$(12) \quad \cos(\alpha + 240^\circ) = -1/2 \cos \alpha + \frac{\sqrt{3}}{2} \sin \alpha$$

We arrive at

$$(13) \quad R = 1.5m \angle \Delta\theta$$

$$\text{where} \quad \Delta\theta = \arctan \left(\frac{-\sin w_m t}{\cos w_m t} \right)$$

The minus sign indicates that the signal phase angle θ is continuously retarded for the relative phase sequences assumed. It may be noted that since m is a constant, the amplitude is constant, at value $=1.5m$. Hence, for maximum output signal amplitude, use 100% amplitude modulation for which $m=1.0$. The change in the signal phase angle, $\Delta\theta$, can be obtained from $\dot{R}$ as follows:

$$(14) \quad \tan \Delta\theta = \frac{\sin w_m t}{\cos w_m t} = -\tan w_m t$$

$$(15) \quad \therefore, \Delta\theta = -w_m t$$

To obtain the change in signal frequency, differentiate $\Delta\theta$ with respect to time:

$$(16) \quad \frac{d\Delta\theta}{dt} = -w_m$$

or

$$(17) \quad \Delta w = -w_m \quad \text{and} \quad \Delta f = -f_m$$

The mathematical derivation shows that the change in signal frequency Δf equals the value of the modulating frequency, f_m . For the relative phase sequences assumed the output frequency is lower in value than the input frequency. By reversing one or the other input phase sequence, the output frequency may be made greater than the input frequency.

The A, B and C components of the unprocessed audio frequency band are applied in parallel to plural channels, of which the described channel may be denominated #1, and the further channels may be #2, #3, #4 and #5. The band pass filter 17a appropriate to channel #2 may have a center frequency twice that of channel #1, i.e., 554 c.p.s., and succeeding channel filters may have center frequencies twice the value for the immediately preceding channels. In each case the channel filter may pass substantially one octaval sub-band, there being obviously some overlap of channels due to the fact that the filters employed do not have infinitely sharp cut-offs. This is advantageous since it permits a smooth transition from one band to the next.

While each succeeding modulation frequency may differ in value by a factor of about 2, it has been found that optimum values by which the processed frequencies may differ from the unprocessed frequencies, for the several channels, may be as follows:

Channel No.	Channel Center Frequency (c.p.s.)	Modulating Frequency (c.p.s.)	Percent Deviation In Frequency
1	277	1.4	-0.5
2	554	2.2	+0.4
3	1108	3.3	-0.3
4	2216	5.5	+0.25
5	4432	8.9	-0.20

The entire audio band need not be processed, according to the present invention, i.e., those frequencies falling below channel #1 in frequency may be transferred directly from source 10 to a lead 20 on which are collected the outputs of the several channel filters, 17, 17a, etc., via a low pass filter 21, while the frequencies falling above channel #5 may be directly transferred via a high pass filter, 21a.

The unprocessed output of source 10 is applied via an amplifier 22 to electro-acoustic transducer 23, while the processed output appearing on lead 20 may be amplified to a suitable level in amplifier 24, and radiated by transducer 25. The acoustic outputs of the two separate sources may be equal, or approximately equal, for maximum musical effect, although desirable effects are also obtained if one or the other output strongly predominates, and the separate sources are, preferably widely, separated.

More particularly, adjacent ones of channels #1-#5, inclusive, may be arranged to provide oppositely directed changes in frequency. Since each channel processes substantially one octave of an audio frequency band, it results that adjacent tones of the same nomenclature may be shifted in frequency in opposite senses, and it is this feature which is of particular value in providing chorus effects. Since the specified effect is obtained by reversing the phase sequence of the modulating signal, in the presently described embodiment of the invention, only two modulating channels are specifically described, corresponding elements in the several channels being identified by the same reference numerals, but with different letter sub-scripts. Accordingly, in channel #2 the amplitude modulators 12a, 13a and 14a are connected to the source of modulating signal 15a in the opposite phase sequence F_2, E_2, D_2 as in the case of amplitude modulators 12, 13, 14, whose modulating phase sequence is D_1, E_1, F_1 .

Referring now more particularly to FIGURE 2 of the accompanying drawings, there is illustrated a circuit diagram corresponding with the system of FIGURE 1, which is in part schematic.

In FIGURE 2 the reference numeral 10 denotes an audio spectrum source or an audio frequency signal input, as in the system of FIGURE 1. The spectrum or frequency band supplied by the source 10 is passed through a cross-over network 30, which selects from the entire source spectrum a relatively restricted band which is to be processed. The high pass portion of 30 feeds phase splitter 31 whereas the low pass portion of 30 feeds the output lead 71. In this manner, intermodulation distortion problems in the subsequent amplitude modulators are minimized. In particular, for the purpose of the present exposition, it is assumed that five octaves of an audio band representing music, will be processed. These bands center on 277 c.p.s., 554 c.p.s., 1108 c.p.s., 2216 c.p.s., and 4432 c.p.s. It will be realized, however, that if desired, further octaves may be processed, and also that while the preferred form of the invention involves the processing of octaval bands in discrete channels, that it may for some purposes be desired to process half octave bands in discrete channels, or in the alternative to process two octaves in a single channel. The invention is in this respect completely flexible, and lends itself well to the requirements of economy of circuitry where that is a primary consideration, by reducing the total number of required processing channels, or to the extension of the number of processing channels where economic factors are of relatively minor importance.

The output of the high pass filter portion of 30, assumed to contain the five octaves above specified, is applied to a conventional 180° phase splitter 31, from the output of which, on two leads 32, 33, are derived two duplicate audio spectra, which differ only in respect to phase of the frequency components of the spectra. The leads 32 and 33 are connected via coupling capacitors 34 and 35

to the input terminals of a four terminal all-pass lattice work 36, having output terminals 37 and 38. The lattice network 36 is a phase shift network, having a flat amplitude response, and which shifts the phase of the signals at the output terminals 37, 38, from their input relation of 180° separation, to a value of 120° separation. The design principles upon which the design of the lattice network 36 is predicated may be found discussed in an article published in the Bell System Technical Journal for January 1950, at page 94, in the name of Sidney Darlington. The output signal on terminal 37 is applied directly to a 180° phase splitter 40. The output signal on terminal 38 is applied directly to the input of a 180° phase splitter 41, and the joint outputs of the terminals 37 and 38 are applied via adding resistances 42 and 43, respectively, to the input of a phase inverter, 44, in parallel. The output of phase inverter 44 is separated 120° from both the signal on terminal 37 and that on 38 and is applied to a 180° phase splitter 45.

The 180° phase splitters 40, 41 and 45 may be essentially duplicate circuits, and accordingly the phase inverters 40 and 41 have been represented as blocks, while the phase splitter 45 is shown in schematic form. Input is applied to the phase splitter 45 via a coupling capacitor 46. The phase splitter 45 includes a triode vacuum tube 47, having an anode load 48 and a cathode load 49, and having also in its cathode circuit a by-passed bias resistance 50. A grid leak 51 is connected directly between the grid and point x, and an output signal is derived from the anode via a coupling capacitor 52 across a suitable resistance 53, connected from the coupling capacitor 52 to ground, and providing thereacross an output signal. Similarly, output signal is derived from the cathode circuit of the triode 47 via a coupling capacitor 55 and an output resistance 56. The anode load 48 and the cathode load 49 are of the same magnitude, as are also the resistances 53 and 56, so that oppositely phased audio spectra, which in respects other than phase are duplicates, are available on terminals labeled C_p and C_k , respectively, the sub-scripts serving to indicate whether the corresponding signals are derived from the plate or the cathode of a phase splitter. Similarly, outputs may be derived from output terminals available at phase splitters 40 and 41. These are identified respectively by the designations B_p and B_k for the phase splitter 40 and A_p and A_k for the phase splitter 41. The relative phase angles of the phasor quantities A , B and C available at the several output terminals of the phase inverters are shown adjacent to the circuit diagram, and it will be evident that the phasor output A has been assigned zero phase, phasors C and B lagging behind A by 120° and 240°, respectively. It will be noted in particular that the plate phasors have the phase sequence A, C, B, as do also the cathode phasors, but that $A_k = A_p \angle 180^\circ$.

In the left of center portion of FIGURE 2 is illustrated in schematic circuit diagram a three phase RC coupled ring oscillator 60. The oscillator 60 includes three triode vacuum tubes 61, 62 and 63. Each of the triodes 61, 62 and 63 is provided with an anode load resistance, these being identified by the numerals 64, 65 and 66. In addition, a load resistance 67 is connected from a B+ terminal 68 to the load resistances 64, 65, 66. Accordingly, at the low voltage terminal 69 of the resistance 67 may be derived a combined signal output. This signal output which is the sum $A+B+C$, after modulation, i.e., $O+P+Q$, is applied to the input of a band-pass filter 70, and passes via the filter 70, to an output lead 71. The band-pass filter 70 is arranged to have a center frequency of 277 c.p.s. and to have a band width of approximately 1 octave.

Connected from each anode of the triodes 61, 62 and 63 to the grid of the adjacent triode is a phase shift network of the RC type, consisting of 76 and 78, respectively, which shifts the phase of a low frequency signal applied

to the following grid relative to that available on any anode by 60°. Because of the further shift of 180° in the succeeding triode stage 61, the low frequency signal at the plate of 61 leads that at the plate of 63 by 120°. The frequency of oscillation, f_m , is given approximately by

$$\frac{\sqrt{3}}{2\pi RC}$$

where R and C are 76 and 78, respectively. The several triodes accordingly oscillate in ring fashion, and at a low frequency for which the phase shift from anode to anode of the several triodes equals 120°, since it is for this frequency alone that the three RC networks and three tube stages will introduce a total phase shift of 360°. The cathodes of the triodes 61, 62, 63 are connected together, and via the common junction 74 to ground through bias resistor 75a. For equality of low frequency phase amplitudes or "balanced" conditions, there is no low frequency alternating current flowing through resistance 75a because of the balanced three phase relationship. Thus, the modulating signal is balanced out and does not appear in the output at 69. The capacitor 75b can therefore be relatively small in value since it need by-pass resistance 75a only at audio frequencies to thus maintain a large value of modulator voltage gain. Similarly, B+ power supply filtering requirements at the low modulating frequencies employed are not a problem since low frequency alternating current does not flow through resistance 67 for balanced conditions.

For audio frequency "balanced" conditions, the three phase audio signals O , P and Q cancel one another at point 69 in the absence of modulation as can be observed in Equation 13. That is, when $m=0$, R also $=0$. Hence, the modulator is of the doubly balanced variety having only a single side band in its output.

Considering a phase shift circuit 76, 78 of oscillator 60 as typical, its mode of operation will be further discussed. It will be observed that from the anode of the triode 63 is connected a resistance 76, which leads directly to the grid of the succeeding triode in the phase sequence, i.e., triode 61. From the grid of the triode 61 is connected a parallel combination of resistance 77 and capacitor 78, which have a common terminal at the grid, and a further terminal 83, which constitutes an audio input terminal for this phase of the oscillator. The terminal 83 may be connected to one of the terminals of one of the phase inverters 40, 41 and 45 and when so connected the output resistance of the phase splitter (such as 53 or 56) constitutes a circuit to ground for the capacitor 78. It is when so connected that the series combination of resistance 76, capacitor 78 and for example, resistance 53, introduce the required phase shift which determines the frequency of operation of the oscillator 60.

In addition to the ring oscillator 60, four further ring oscillators are provided, which are identified by the reference numerals 90, 91, 92 and 93, respectively. These each follow broadly the design principles upon which the oscillator 60 is predicated, but involve different circuit parameters, so that the frequency of oscillation of each of the oscillators is different from that which precedes it in the sequence. The considerations upon which is based selection of oscillating frequencies for the several oscillators has been above discussed, and accordingly is not repeated at this point. The output of oscillator-modulator 90 is passed through a band pass filter 95, having a center frequency of 554 c.p.s. and a band pass of one octave. Associated with the oscillator 91 is an output band-pass filter 96 having a center frequency of 1108 c.p.s. and a band width of one octave. Associated with the oscillator 92 is a band-pass filter 97 having a center frequency of 2216 c.p.s., and a band-pass of one octave, and associated with the oscillator 93 is still another band-pass filter 98, having a center frequency of 4432 c.p.s. and a band width of one octave. Accordingly, the several

band-pass filters 70, 95, 96, 97, 98, in parallel, pass a complete band of frequencies, comprising five octaves. There is overlap at the cross-over points of the filters and careful choice of the amplitude versus frequency characteristic of each band-pass filter permits a smooth transition in frequency shift accomplished by the modulators over the wide, five octave band. The alternate use of what may be termed plate phase and cathode phase obtained from the phase splitters 45, 40, 41 further assists in this desired smooth transition. The outputs of filters 70, 95, 96, 97 and 98 are all connected to the lead 71, so that from the lead 71 proceeds what has been termed hereinabove a processed musical spectrum, or a processed tone, and in this respect the output lead 71 of FIGURE 2 corresponds with the output lead 20 of FIGURE 1.

We may now assume that the output terminals of the phase splitters 45, 40 and 41, which are labeled C_p , C_k , B_p , B_k and A_p , A_k , in FIGURE 2, are connected to the input terminals of the ring oscillators 60, 90, 91, 92 and 93, by connecting together correspondingly labeled terminals. Considering any one triode, such as 61, there is applied to its grid circuit via the terminal B_p , a wide band audio spectrum, and also by virtue of the action of the oscillator itself there is applied to the grid of the triode 61 a generally sinusoidal sub-audio signal, which may have a value of approximately 1.4 c.p.s. in the case of oscillator 60. The relatively large swing in grid voltage accomplished by the low frequency oscillations changes the operating point so that the small signal audio frequency voltage gain varies over wide limits. Thus, a combined function of oscillator and modulator is accomplished in one circuit. Capacitor 78 serves two other useful purposes besides its role in the low frequency phase shift network. It serves to by-pass grid leak resistor 77 so that the effect of variable input or "Miller" capacitance of the tube, which would cause unwanted phase shifts, is minimized. Furthermore, it prevents audio frequency degeneration around the ring which would decrease the voltage gain of the modulator. The grid leak resistances, such as 77, are selected to have a value considerably larger than the common output resistances of phase splitters 40, 41, and 45, such as resistances 53 and 56, so as to accomplish decoupling between the low frequency oscillators which are to act independently of one another. It follows that the amplitude of the audio band will be modulated by the sub-audible signal, and if the relative amplitudes of the signals are suitably chosen, as they are in the design of the present system, the total range of amplitude variation of the audio frequency spectrum will be from substantially zero to a value equal to twice the unmodulated amplitude of the audio spectrum. The same sequence of events occurs generally in each of the triodes of each of the ring oscillators, but in any given ring oscillator, the phase sequence of the audio signals applied to the input terminals may be the same as, or opposite to, the phase sequence of the sub-audio modulating signals generated by the ring oscillator. It has been shown, hereinbefore, and it will be clarified by reference to phasor diagrams hereinafter, that the net result of amplitude modulating, in three phase relation, the three phases of an audio frequency band, is to generate a rotating phasor, of continually increasing or decreasing phase for each frequency of the audio band, depending on the relative phase sequences of the two sets of signals. The rate of phase increase or decrease is constant, and accordingly, the phase increase or decrease represents either a positive or a negative change in frequency. Accordingly, each modulator oscillator introduces at its output terminal (69 in the case of oscillator 60), a frequency shifted version of the input audio spectrum, i.e., each frequency of the output spectrum is frequency shifted by the same amount, and the frequency shift will be either positive or negative depending upon the relative phase sequencing employed between the audio band and the sub-audio modulating signal.

Examination of the phase sequences employed in the system illustrated in FIGURE 2 indicates that the frequency shifts introduced in alternate channels are of opposite signs. This results from applying the phases, reading from left to right in modulator-oscillator 60 of B_p , A_p , C_p , while in modulator-oscillator 90, it is A_k , B_k , C_k . It will be noted that alternate modulator oscillators of the sequence 60, 90, 91, 92, 93, are connected to plate and cathode output terminals, of the phase inverters 45, 40 and 41. The phase sequence for the outputs of the phase inverters 45, 40, 41 does not change when connection is made to the plates or P terminals rather than to the cathode or k terminals, but rather all phasor quantities are shifted in phase 180° . This interchange of connections does not imply an inversion of the algebraic sign of the frequency shift, but does modify the phase of any audio frequency, in a modulated frequency band, by 180° . The alternate connection of the ring oscillators to plate and cathode terminals of the phase inverters, therefore, accomplishes the result that adjacent frequencies deriving from any two adjacent sub-bands or octaves, are co-phased rather than of opposite phase. This scheme permits a smooth transition, with regard to frequency shift as well as amplitude response, between the overlapping band-pass filters.

Reference is now made to FIGURE 6 of the accompanying drawings, wherein is shown the resultant phasor R, of the three phasors, O, P and Q, for various instants of time in the period of the sub-audible modulating signal which differ by 60 electrical degrees.

The magnitude of the separate phasors has been drawn approximately to scale and it may be perceived, on a qualitative basis, that the resultant R rotates clock-wise, achieving a 60° rotation for each increment of time in the period of the modulating signal portrayed while remaining constant in amplitude. The quantitative appreciation of the phasor diagrams of FIGURE 6 may best be accomplished by considering the phasors as pictorial representations of Equations 1, 2, 3, 4 and 13 in the mathematical development about provided, wherein the observer is considered to be rotating at the origin of the system at the signal angular velocity, so that O, P and Q, appear to the observer to have fixed angular positions, and wherein the modulating signals accordingly serve to vary the lengths of these phasors, thereby to change the angle of the resultant phasor at a rate equal to the angular velocity of the modulating source.

Although the specific modulator of this application is all-electronic, as hereinbefore mentioned, it will be obvious to one skilled in the art that the scope of my invention may include electromechanical or other suitable types of modulators. For example, the artificial-line scanning device disclosed by Hanert in U.S. Patent 2,382,413 may be employed as the modulation means.

While I have described my invention in terms of a preferred embodiment thereof, it will be realized that variations and modifications of the system, and of the details thereof, may be resorted to without departing from the true spirit and scope of the invention as defined in the appended claims.

What I claim is:

1. A system for frequency shifting a band of audio frequencies representative of music, comprising means for deriving from said band of audio frequencies further bands of audio frequency signals the frequencies of which duplicate the frequencies of the first-mentioned band of audio frequencies but are relatively displaced in n equal phases, where n is greater than 2, a source of n -phase sub-audio frequency and means operatively associated with said first means and with said source and responsive to each phase of said n -phase sub-audio frequency for modulating the amplitude of one of said n further bands of audio frequency signals.

2. The combination according to claim 1, wherein the value of n is three.

3. The combination according to claim 1, wherein said source of n -phase sub-audio frequency is an n -phase ring oscillator.

4. The combination according to claim 1, wherein said source of n -phase sub-audio frequency is an n -phase ring oscillator having at least one unilateral control device per phase, and means for coupling each of said further bands of audio frequency signals to a separate one of said unilateral controlling devices in amplitude modulating rotation.

5. In a system for frequency shifting each frequency in a single multiple frequency audio channel a predetermined percentage frequency deviation wherein said frequencies have a spectrum which may include, at random, low and high audio frequencies, a single filter device arranged for deriving from said single audio channel two frequency bands duplicating said spectrum in respect to frequency and amplitude and having corresponding frequencies separated by substantially 120° , means operatively associated with said filter device for deriving from said two frequency bands by phasor addition, a third frequency band duplicating said spectrum in respect to frequencies and amplitude and having each frequency separated in phase from a corresponding frequency in either of said two frequency bands by 120° .

6. In a system for frequency shifting the entire frequency content of an audio frequency band representing music by approximately the same percentage deviation, means for frequency shifting the entire frequency content of said audio frequency band in each of a plurality of separate channels by a predetermined different frequency shift, and means operatively associated with said first means for selecting from each of said channels a relatively narrow sub-band of frequencies having substantially said percentage deviation over said sub-band.

7. In a system for frequency shifting sub-bands of an audio frequency band representing music each by a predetermined percentage deviation, means for frequency shifting the entire audio frequency band in a plurality of separate channels so that a different one of said sub-bands in each separate channel is frequency shifted substantially by the predetermined percentage deviation appropriate to that sub-band and means operatively associated with said first means for abstracting from each of said channels only the sub-band which is frequency shifted substantially by the predetermined percentage deviation appropriate to that sub-band.

8. The combination according to claim 7, wherein the percentage frequency deviation for all said sub-bands is substantially the same.

9. The combination according to claim 8, wherein the percentage frequency deviation for at least one of said sub-bands is different from the percentage frequency deviation for another sub-band.

10. A system for simultaneously frequency shifting two adjacent sub-bands of an audio frequency band representing music in opposite senses, wherein said audio frequency band consists of a plurality of said sub-bands, comprising means for shifting all the frequencies of said audio frequency band in a positive sense to provide a positively shifted audio frequency band, means for shifting all the frequencies of said audio frequency band in a negative sense to provide a negatively shifted audio frequency band, and means operatively associated with said first means and said second means for deriving adjacent ones of said sub-bands from alternate ones of said positively and negatively shifted audio frequency bands.

11. In a device for processing tones, a source of a tone having frequency components in different sub-bands of an audio frequency spectrum, means operatively associated with said source for differently and continuously phase rotating frequency components of the different sub-bands always in a single sense only to provide differently frequency shifted frequency components in different sub-bands, means operatively associated with said first means

for combining said frequency shifted frequency components to provide a processed tone, and means operatively associated with said second means for acoustically transducing said processed tone.

12. In a device for processing tones each comprised of frequency components, means for shifting the frequency of each of said components continuously in a single sense only, the frequency shift for each component being substantially the same predetermined percentage of the unshifted frequency of that component, means operatively associated with said first means for combining the frequency shifted components, and means operatively associated with said second means for acoustically radiating sound corresponding in frequency with the frequency shifted components.

13. The combination according to claim 12, wherein is provided means for further concurrently radiating sound corresponding in frequency with said first-mentioned components.

14. In a system for processing a wide band audio spectrum of frequencies corresponding with music, means for deriving from said audio spectrum a plurality of spectra having corresponding frequencies and amplitudes, corresponding frequencies of said spectra being symmetrically phase separated, and means operatively associated with said first means for amplitude modulating each of said spectra in response to plural modulating frequencies of such phases and amplitudes as to generate continuously changing phase shifts of the sums of the symmetrically phase separated spectra in given senses and at uniform angular velocities determined by the frequencies of said modulating frequencies.

15. The combination according to claim 14, wherein is provided means operatively associated with said second means for deriving from each of the continuously phase shifting sums of the symmetrically phase separated spectra a relatively narrow band of frequencies having a predetermined approximately constant percentage frequency deviation over the relatively narrow frequency band.

16. The combination according to claim 14, wherein is provided means operatively associated with said second means for deriving from each of the continuously phase shifting sums of the symmetrically phase separated spectra a different sub-band of signals having a width of the order of one octave.

17. In a system for processing an audio frequency band consisting of sub-bands each having a width of approximately one octave and center frequencies f , $2f$, $4f$, $8f$ and $16f$, means for separately frequency shifting said sub-bands as a whole by amounts of the order of $\pm\Delta f$, $\pm 2\Delta f$, $\pm 4\Delta f$, $\pm 8\Delta f$ and $\pm 16\Delta f$, respectively, and means operatively associated with said first means for combining the frequency shifted sub-bands to form a frequency shifted audio frequency band having substantially a constant percentage frequency deviation, wherein $\pm$ implies only one of plus and minus, and f is an audible frequency.

18. In a system for processing an audio frequency band representative of music, said band consisting of sub-bands each having a width of approximately one octave and said sub-bands having approximately octavely related center frequencies, means for frequency shifting each of said sub-bands as a whole by a different one of a plurality of fixed sub-audio frequency shifts, wherein said shifts increase in a series and wherein succeeding absolute values of said series exceed immediately preceding values by substantially a factor of two, and means operatively associated with said first means for combining the frequency shifted sub-bands to provide a processed audio frequency band.

19. The combination according to claim 18, wherein adjacent values in said series of said sub-audio frequency shifts are of alternate algebraic sign.

20. The combination according to claim 19, wherein is provided means for jointly acoustically transducing said processed audio frequency band and the first-mentioned audio frequency band.

21. A system for processing a band of audio frequencies consisting essentially of a plurality of musical semi-tones, each of said semi-tones including at least a fundamental frequency component and partials thereof, comprising means for differently modifying the frequencies of a plurality of said separate electrical fundamental frequency components to provide separate differently modified musical components, and means operatively associated with said means for modifying for acoustically reproducing said processed musical components, wherein said means for differently modifying includes separate modulators for phase rotating the frequencies of different ones of said semi-tones respectively in positive and negative sense only, and any given semi-tone in only one of said senses.

22. A system for processing a band of audio frequencies consisting essentially of a plurality of musical semi-tones, each of said semi-tones including at least a fundamental frequency component and partials thereof, comprising means for frequency shifting to a constant extent in one sense only as a function of time the frequencies of a plurality of said separate electrical fundamental frequency components to provide separate differently modified musical components, and means operatively associated with said means for modifying for acoustically reproducing said processed musical components, the frequency shifts being different for different ones of said fundamental frequency components.

23. A system for processing a band of audio frequencies comprising a plurality of musical semi-tones, each of said semi-tones including at least a fundamental frequency component, comprising filters for separating into separate channels certain of said fundamental frequencies, means operatively associated with said filters for separately frequency shifting to constant extents in a single given sense only and in relatively different fashions the frequencies contained in each of said channels so as to provide processed musical semi-tones, and means connected to said means for separately modifying for combining the modified outputs of said channels to provide a processed band of audio frequencies representing music.

24. A system for processing a band of audio frequencies, comprising a source of a plurality of musical semi-tones, each of said semi-tones comprising a fundamental frequency and a plurality of harmonic frequencies, a plurality of band pass filters operatively associated with said source and having different center frequencies and connected in parallel to said source of a plurality of musical semi-tones, each of said band-pass filters arranged and adapted to have a pass frequency band equal to at least a semi-tone, means coupled to said filters for differently musically frequency shifting in one sense only the frequencies of the signal outputs of at least some of said filters, and means operatively associated with said means for modifying for combining the musical signals provided by said means for differently modulating.

25. The combination according to claim 24 wherein said means for modifying includes a modifying signal generating device for generating a signal having a characteristic approximately proportional to the frequency of the modified signal for modifying each signal output of each of said filters to an extent approximately proportional to the frequency of the signal output.

26. The combination according to claim 24 wherein said means for modifying is a means for frequency modulating.

27. The combination according to claim 24 wherein said means for modifying is a means for modifying the frequencies of the signal outputs of all of said filters.

28. A modulation system for a source of a signal spectrum representative of music, each tone of which includes a fundamental frequency and multiple harmonics, comprising modulators coupled in parallel to said source for differently musically shifting in single senses only and

by fixed amounts the frequencies of said fundamental frequencies and of each of said multiple harmonics.

29. A modulation system for a musical spectrum, comprising a source of a band of frequencies representative of a musical spectrum, and comprising for each semi-tone a fundamental frequency and a plurality of partials, filter means coupled to said source of a band of frequencies for separating a fundamental frequency deriving from one semi-tone and partials deriving from other semi-tones into a common channel, and means for musically frequency modulating the frequency content of said common channel, wherein said means for frequency modulating is a means for differently frequency shifting in given senses invariable as a function of time frequencies of said fundamentals and of said partials.

30. A modulation system for a musical spectrum, comprising a source of a band of frequencies representative of music, said band of frequencies comprising the frequency of at least one musical semi-tone and multiple partials of said frequency of at least one musical semi-tone, separate filters operatively associated with said source for separating into different channels said frequency of at least one musical semi-tone and at least one of said partials, and means operatively associated with said separate filters for modulating the separate frequencies passed by said filters in relative asynchronism while maintaining the musical character of the last named frequencies, said means for modulating the separate frequencies being means for shifting the separate frequencies differently but each by a fixed amount in a given sense only.

31. A modulation system for a musical tone, said musical tone comprising plural frequencies, comprising means for frequency shifting in one sense by an amount invariable as a function of time the frequency of one of said plural frequencies, means for frequency shifting in one sense by an amount invariable as a function of time the frequency of another of said plural frequencies to different extent than said one of said plural frequencies.

32. A modulation system for a musical tone, said musical tone comprising plural frequencies, comprising means for frequency shifting in one sense by an amount invariable as a function of time the frequency of one of said plural frequencies, means for frequency shifting in one sense by an amount invariable as a function of time the frequency of another of said plural frequencies to different extent than said one of said plural frequencies, the frequency shifts being respectively in opposite senses.

33. A modulating system for a musical tone, said musical tone comprising plural frequencies covering a band of frequencies, comprising plural filter means together co-extensive with said band of frequencies, means operatively associated with said filters for differently musically frequency shifting by frequency increments of fixed extent and sign, the signals passed by each of said filters, said filters having pass band characteristics that overlap sufficiently that at least some of said frequencies will pass through at least two filters with appreciable amplitude but in different phase relationship, and means operatively associated with said filters for combining the outputs of all the filters.

34. A modulation system for a band of frequencies representative of music, said band of frequencies divisible into substantially adjacent sub-bands, comprising means for separating said sub-bands into separate channels, and means operatively associated with said means for separating for individually musically shifting in frequency to fixed extent and in predetermined sense only the frequency content of each of said channels.

35. The combination according to claim 34 wherein is further provided means operatively associated with said means for musically shifting in frequency to fixed extent and in predetermined sense only for combining the modified frequency content of said channels in a single path.

36. The combination according to claim 34 wherein is further provided means operatively associated with said

means for musically shifting in frequency to fixed extent and in predetermined sense only for acoustically radiating signals corresponding in frequency content with the modulated frequency content of said separate channels into a common space.

37. In a system for processing original audio signals representative of tonal output of an electronic organ, means for shifting said audio signals in frequency by a fixed increment in a predetermined sense only, said increment falling in the range of 0.5 c.p.s. to 15 c.p.s. to provide processed audio signals, and means for acoustically transducing said original audio and said processed audio signals concurrently into a common space.

38. In a system for processing original audio signals representative of tonal output of an electrical musical instrument, means for shifting certain of said audio signals in frequency by a fixed increment in one predetermined sense only, means for shifting others of said audio signals by a fixed increment in an opposite predetermined sense only, and means for acoustically transducing the frequency shifted audio signals concurrently into a common space.

39. The combination according to claim 38 wherein is provided means for also acoustically transducing said original audio signals into said common space.

40. In a system for processing an original audio band representative of tonal output of an electrical musical instrument, means for only and always reducing the frequencies of first portions of said audio band, means for only and always increasing the frequencies of other portions of said audio band, and means for both reducing and increasing by invariable amounts in fixed senses only the frequencies of still other portions of said audio band, and means operatively associated with said means for increasing and reducing for acoustically reproducing the frequencies so increased and decreased in frequency.

41. In a system for processing audio signal representative of music, and including substantially harmonically related frequencies, plural frequency modulators respectively operative to shift said harmonically related frequencies contained in said audio signal always in opposite senses respectively, and means connected to said plural frequency modulators for acoustically transducing the frequency shifted frequencies into a common space.

42. The combination according to claim 41 wherein is further provided means for acoustically transducing said first mentioned audio signal into said space.

43. The combination according to claim 41 wherein said frequency shifts are each of fixed amount in a given sense only.

44. The combination according to claim 41 wherein

the extents of said shifts are different for the separate harmonically related frequencies.

45. An audio modulation system for differentially frequency shifting different portions of the entire frequency content of an audio frequency band representing music, which comprises the steps of frequency shifting the audio frequency band in single senses only of a plurality of separate channels by a predetermined amount which is different in each channel from that of any other channel, and selecting from each of said channels a relatively narrow sub-band of frequencies, said sub-bands all having substantially the same percentage frequency deviation.

46. An audio modulation system comprising at least one first source of audio frequency, means operatively associated with said source for deriving at least three frequency bands of the same frequency content but of relatively shifted phases, a second source of sub-audio frequencies, means operatively associated with said second source for deriving at least three frequency bands of the same frequency content but of relatively shifted phases, frequency shift modulator means for combining said relatively phase shifted second bands with said relative phase shifted first bands, and means for electro-acoustically transducing signals from said first source and from said combined bands to thereby produce a chorus effect.

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