United States Patent

Miller

[15] **3,644,657**

[45] **Feb. 22, 1972**

[54] ELECTRONIC AUDIOFREQUENCY MODULATION SYSTEM AND METHOD

[72] Inventor: **Francis A. Miller,** 6600 N.W. 39th Expressway, Bethany, Okla. 73008

[22] Filed: **Oct. 20, 1969**

[21] Appl. No.: **868,294**

Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 771,900, Oct. 30, 1968, abandoned.

[52] **U.S. Cl.** **84/1.25,** 84/DIG. 4
[51] **Int. Cl.** **G10h 1/04**
[58] **Field of Search** ..... 84/1.25, 1.01, 1.18, 1.24, 84/1.11, 1.19, DIG. 4, DIG. 6; 179/1; 332/9.16

[56] **References Cited**

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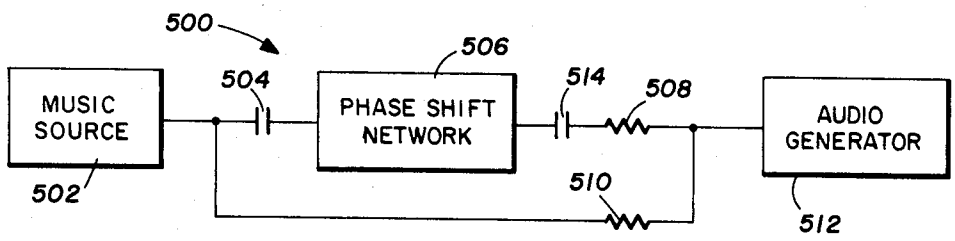
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Primary Examiner—William H. Beha, Jr.
Assistant Examiner—R. Skudy
Attorney—Richards, Harris & Hubbard

[57] **ABSTRACT**

The invention is directed to modulation of the amplitude and frequency of an audiofrequency signal by passing the signal through at least two parallel channels, with phase-shifting circuitry in the channels providing signals of opposed phases. A low-frequency band is filtered from the signal in one of the channels and a high-frequency band is filtered from the signal in another of the channels and the signals shifted back into phase. The filtered signals are then combined into an output signal. The high- and low-frequency bands filtered from the signals are selectively varied to induce vibrato, tremolo, and other tonal effects into the output signal. In a preferred form of the invention, the high- and low-pass filters are matched so as to form substantially a 180° phase shift stage with a flat frequency response. Four stages are coupled to provide 720° of phase shift. The original audiofrequency signal is then summed with the phase-shifted signal in approximately equal proportions to produce a coordinated effect substantially duplicating that produced by a rotating speaker. The phase shift is started and stopped in a manner to duplicate the dynamic effects of starting and stopping a rotating speaker. A dual channel system is described for duplicating a multiple speaker system.

37 Claims, 20 Drawing Figures



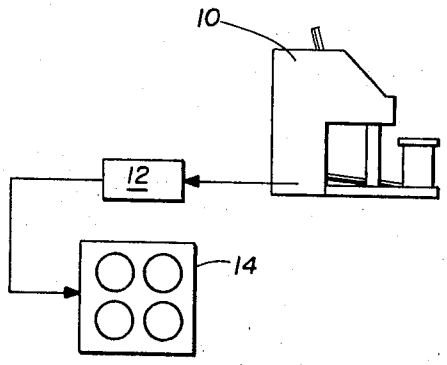


FIG. 1

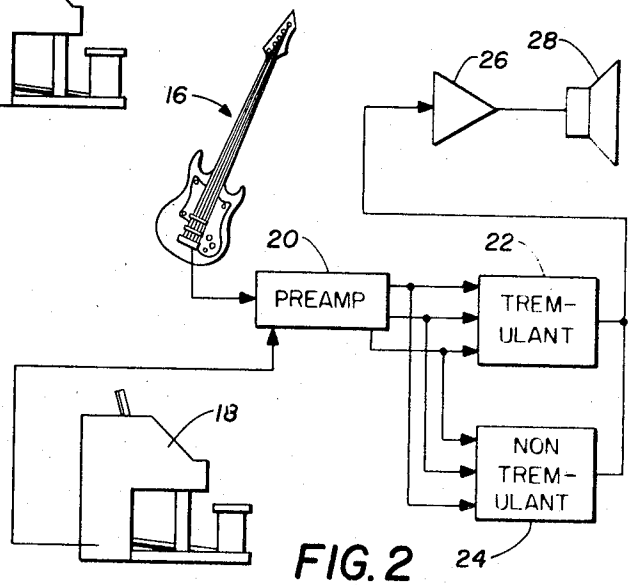


FIG. 2

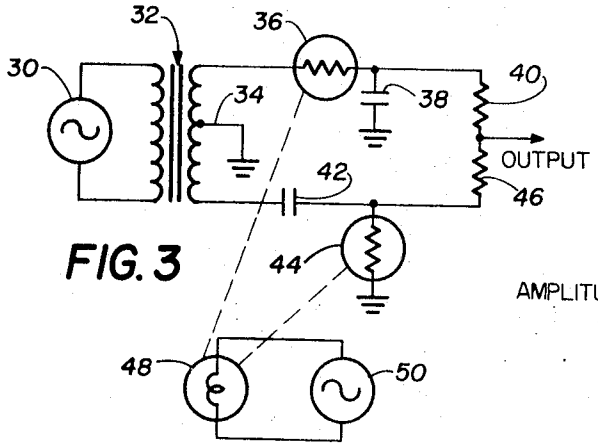


FIG. 3

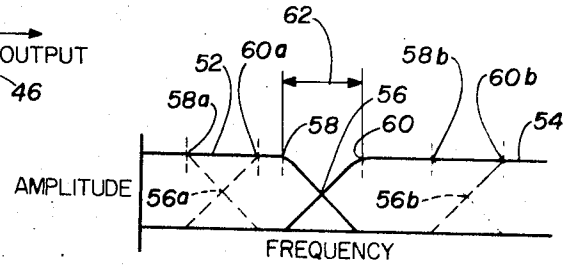


FIG. 4

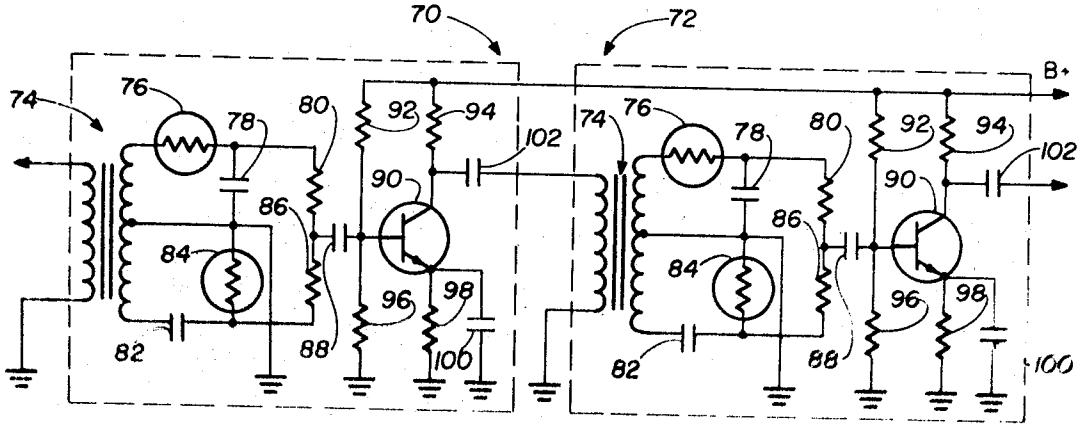


FIG. 6

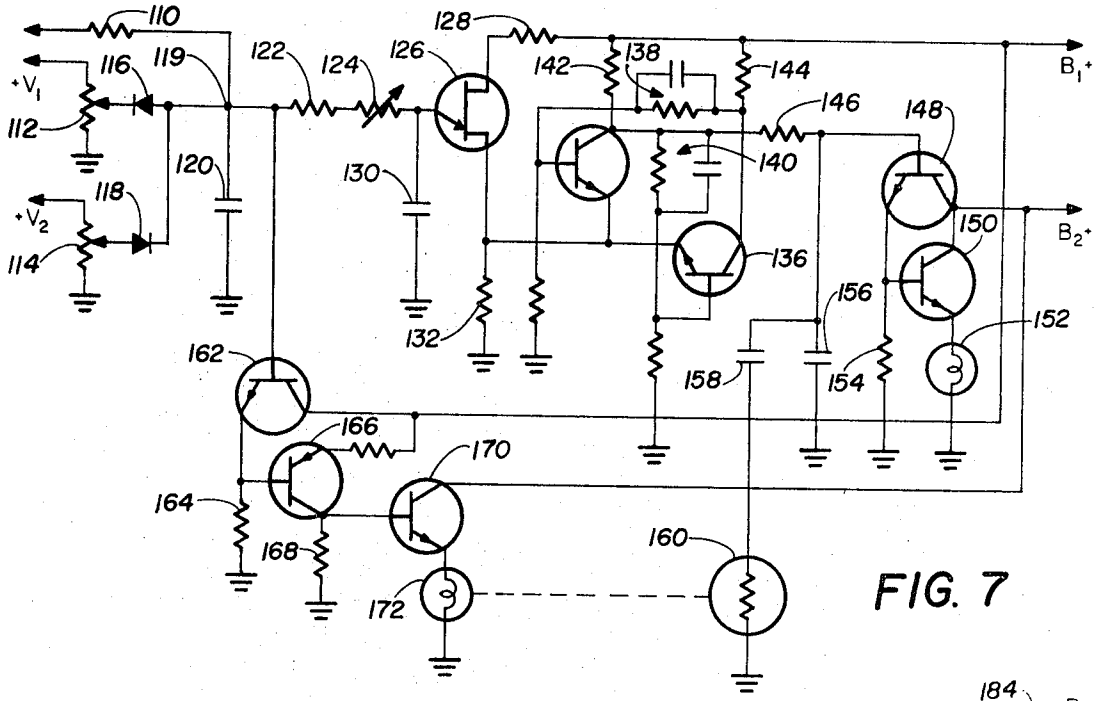


FIG. 7

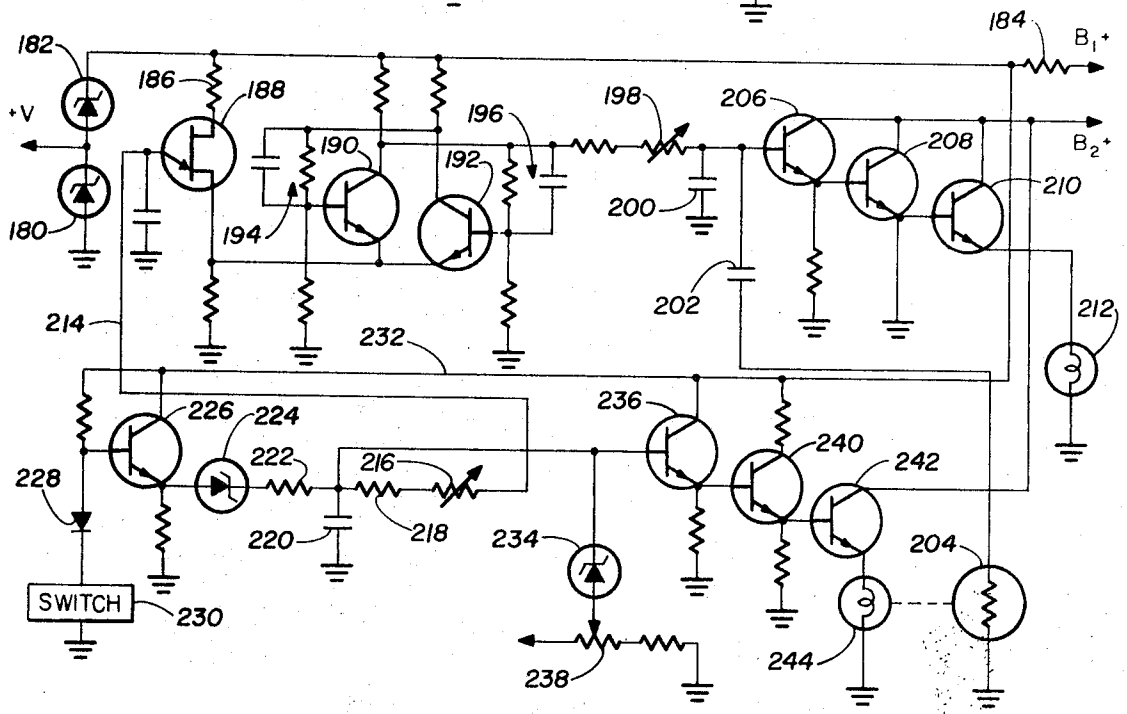


FIG. 8

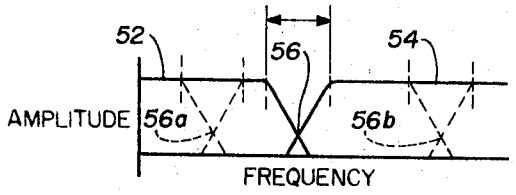
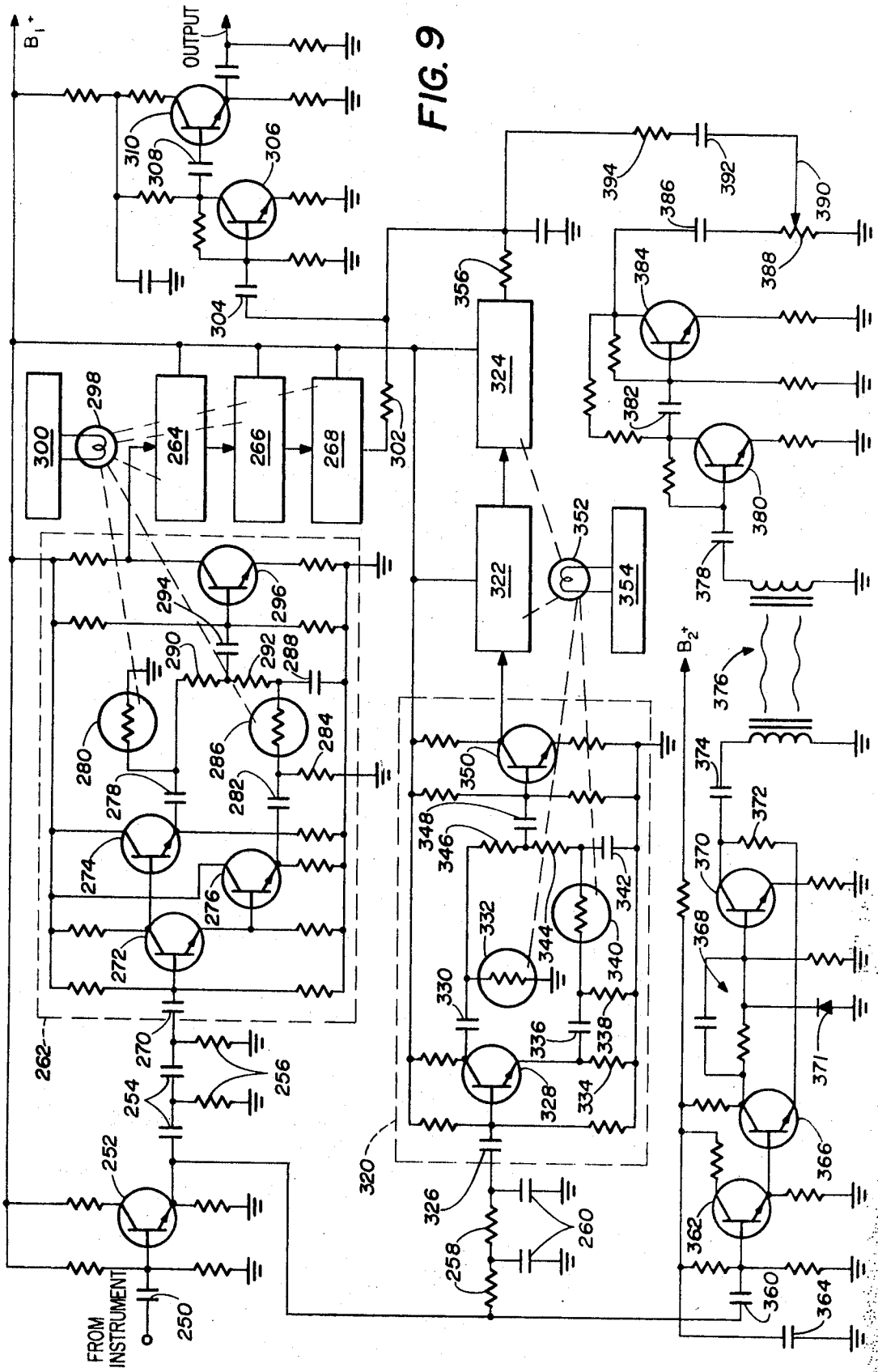


FIG. 5

FIG. 9


B1+
OUTPUT
310
308
306
304
300
298
264
266
268
302
324
356
394
392
386
390
388
384
382
380
378
322
352
354
B2+
376
374
372
370
368
371
366
362
360
364
294
296
290
292
288
280
286
284
278
282
274
276
272
262
270
254
256
252
FROM INSTRUMENT
250
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260

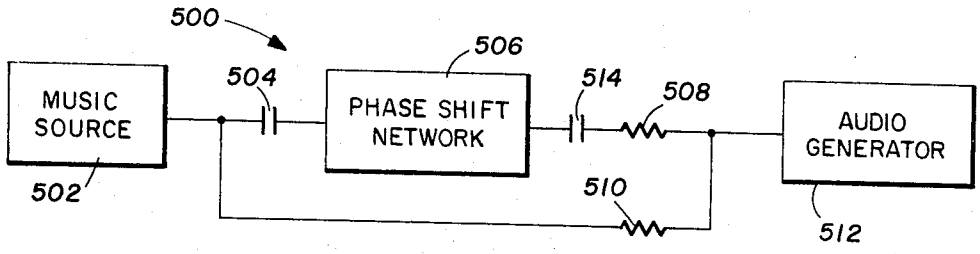


FIG. 10

PRIOR ART

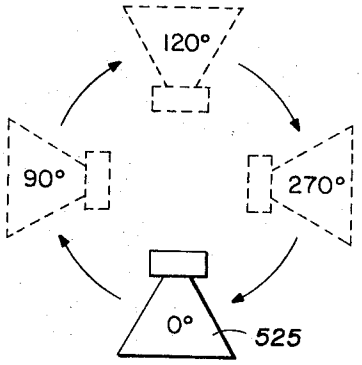


FIG. 11

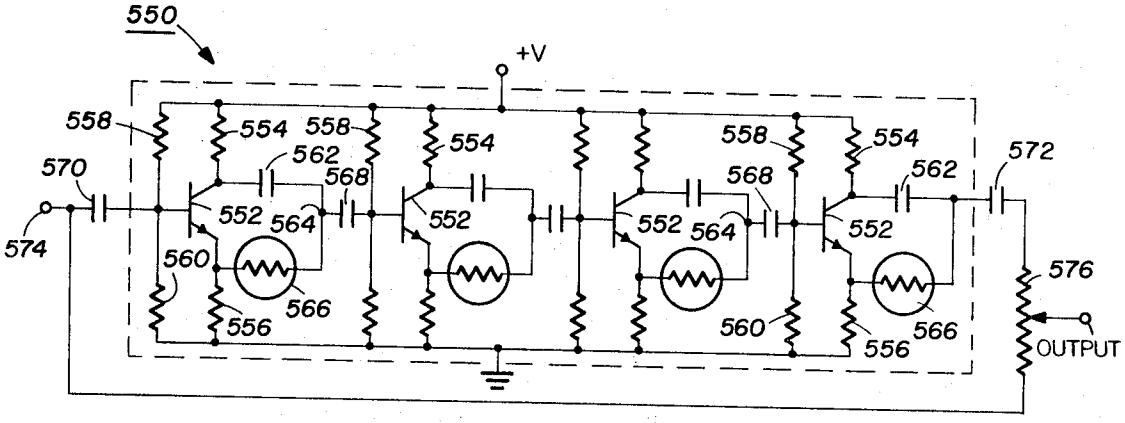


FIG. 18

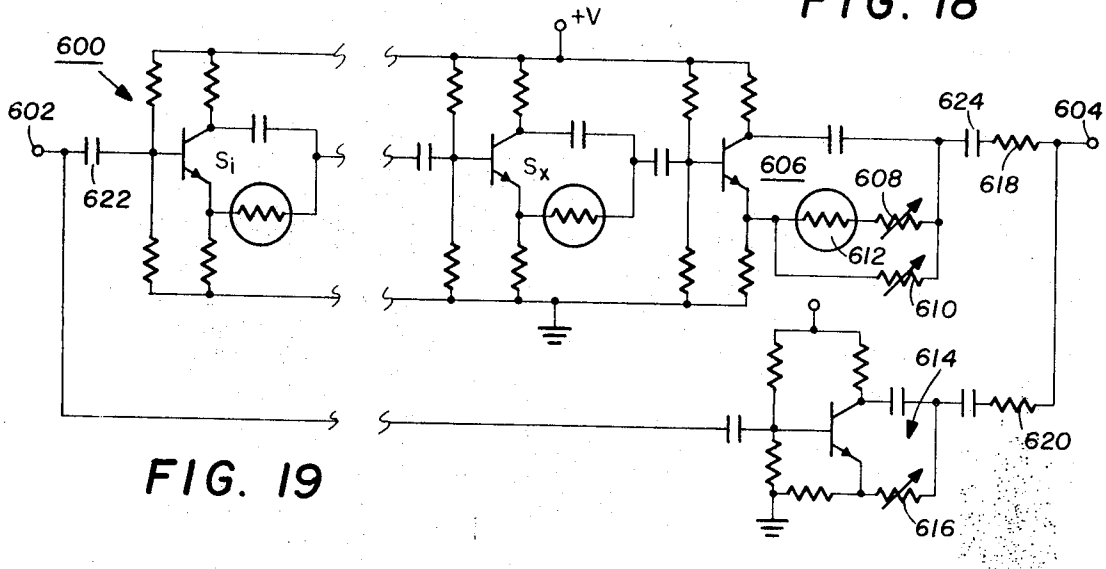


FIG. 19

FIG. 12

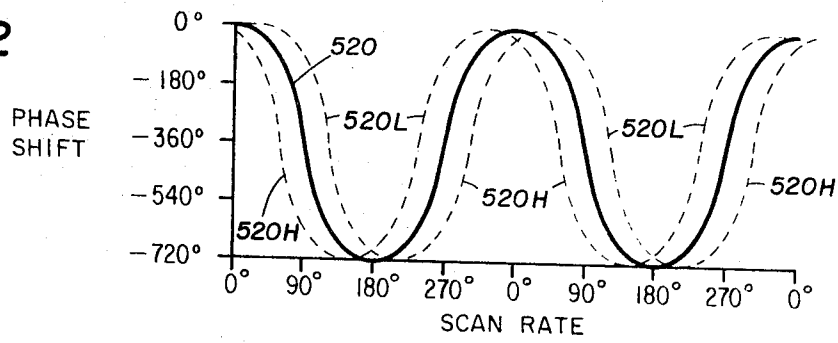


FIG. 13

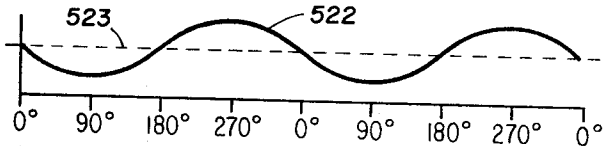
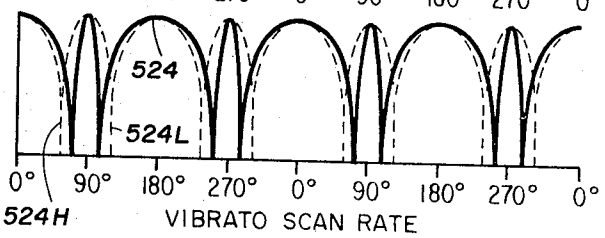


FIG. 14



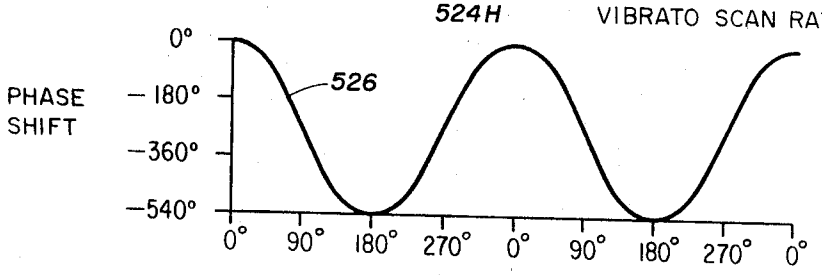


FIG. 15

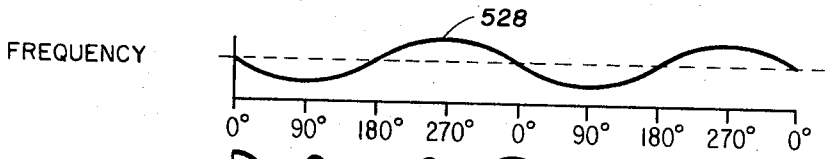


FIG. 16

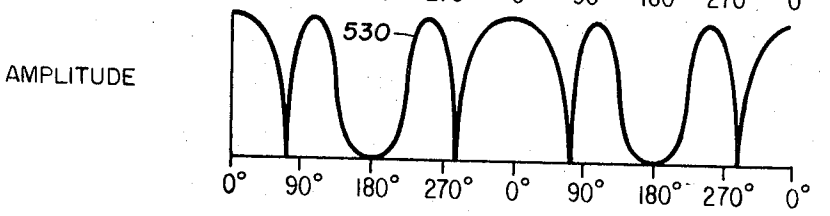


FIG. 17

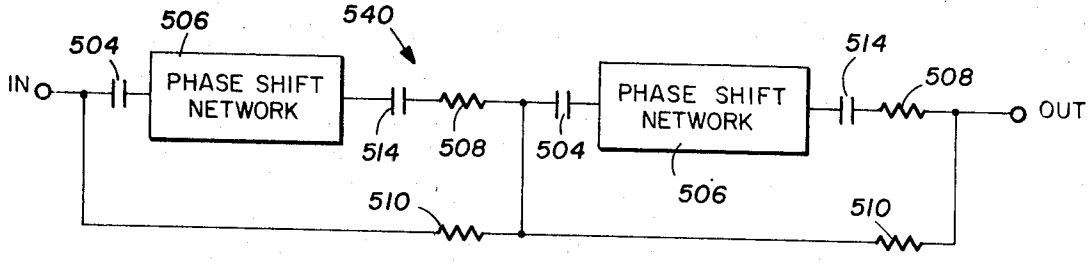


FIG. 20

ELECTRONIC AUDIOFREQUENCY MODULATION SYSTEM AND METHOD

This is a continuation-in-part of application Ser. No. 771,900 filed on Oct. 30, 1968, now abandoned.

This invention relates to method and apparatus for modulating an electrical signal, and more particularly to a method and apparatus for inducing vibrato and tremolo into audio frequency musical signals.

THE PRIOR ART

It has long been known that the introduction of vibrato and tremolo into musical sound provides pleasing musical effects. Vibrato is generally defined as a relatively low-rate modulation of the frequency of a sound about a mean frequency, whereas tremolo refers to a relatively low-rate modulation of the amplitude or intensity of sound. For simplicity of description, the word tremulant is often used in a general manner to refer to variations of tonal quality of audiofrequency signals, including both vibrato and tremolo. In practice, the tremulant modulation rate utilized in musical performances is within the range of about 1 to 15 cycles per second.

A number of electronic circuits have been heretofore developed for the introduction of tremulant effects into the electrical output of a musical instrument, such as an organ. For instance, amplifiers have been previously utilized in which the output of an oscillator is amplitude modulated by such circuitry as to control grids of a push-pull output stage. Other oscillator circuits using filtering of various frequency bands have also been proposed, such as the system described in U.S. Pat. No. 3,205,294, issued Sept. 7, 1965. Systems have also been developed wherein a tremulant effect is induced by filtering a signal while varying the frequency response of the filter. Examples of such circuits are described in U.S. Pat. No. 3,388,257, issued June 11, 1968. However, such electronic modulation circuits heretofore developed have not enjoyed widespread use in the general music field, as the number and quality of tonal effects which may be created with the circuits are limited, and additionally because many of the circuits have not been adaptable for use with a variety of musical instruments.

Primarily because of the lack of an adequate electronic substitute, extensive use is presently made of mechanical tremulant devices wherein audio frequency signals are modulated by rotating loud speakers, sound channels, or sound reflectors. An example of one such well-known mechanical tremulant device commonly termed the Leslie speaker is disclosed in U.S. Pat. Re. 23,323 issued to D. J. Leslie. Not only are rotating mechanical modulation devices useful in introducing tremolo and vibrato into musical programs, but a number of distinctive musical effects may be produced by such devices due to the starting and stopping dynamics of the mechanically rotated parts in the devices. Often during performance of certain musical compositions, such rotating mechanical devices are purposefully turned off and on a number of times to produce unusual musical effects. However, rotating mechanical devices are not only extremely bulky and expensive, but are subject to mechanical failures of the rotated parts therein.

In one embodiment of the invention, the tremulant effect produced by a rotating speaker is closely simulated by a plurality of high and low pass filter stages connected in cascade. The amplitude of the pass bonds of the filters are slightly mismatched so as to provide amplitude modulation in synchronism with the frequency modulation produced by the phase shift resulting from the stages. In accordance with another aspect of the invention, the vibrato rate is set at two different levels and a means provided for changing from one rate to the other in a manner to duplicate the musical effects introduced by the inertial characteristics of a rotating speaker.

In accordance with another embodiment of the invention, phase shift is introduced to the musical signal without significantly changing the amplitude, then the original signal is summed with the phase-shifted signal to provide amplitude modulation by cancellation. In a preferred form of this embodiment, the original signal has an amplitude from about 0.5 to about 1.5 that of the phase-shifted signal, and has a total phase shift of at least about 720°. Best results are obtained with a phase shift angle that is an even multiple of 360°.

In accordance with one aspect of the invention, different frequency bands are filtered from a plurality of parallel phase shifted audiofrequency signals and then the filtered signals are combined. The frequency bands filtered from the phase-shifted signals are selectively varied in order to induce tremulant effects into the signals.

In another aspect of the invention, a plurality of parallel channels generate outputs which are added to provide a modulated audiofrequency output signal. Each of the channels comprises filters for filtering upper and lower frequency bands from a plurality of parallel signals having opposed phases. The frequency responses of the filters are selectively variable so that the crossover frequencies of the frequency responses of the filters are varied to induce modulation of the output signals. The rate of variance of the frequency responses of filters of different channels may be selectively changed to produce interesting musical effects.

For a more complete understanding of the present invention and for further objects and advantage thereof, reference is now made to the following description taken in conjunction with the accompanying drawings, in which:

FIG. 1 is a diagrammatic illustration of one utilization of the tremulant system according to the invention;

FIG. 2 is a diagrammatic illustration of another use of the tremulant circuit of the invention;

FIG. 3 is a schematic diagram of one embodiment of the present tremulant circuit;

FIG. 4 and 5 are diagrammatic waveforms illustrating different modes of operation of the circuit shown in FIG. 3;

FIG. 6 is a schematic diagram of another embodiment of the invention;

FIG. 7 and 8 are schematic diagrams of different embodiments of circuits for driving the variable light sources of the invention;

FIG. 9 is a schematic diagram of another embodiment of the present tremulant system;

FIG. 10 is a schematic block diagram of a system in according with the present invention;

FIG. 11 is a schematic diagram which assists in describing how the circuit of FIG. 10 duplicates the sound of a rotating speaker;

FIGS. 12, 13, and 14 are grafts of the phase shift, frequency modulation, and amplitude modulation produced by a preferred embodiment of the system illustrated in FIG. 10;

FIGS. 15, 16, and 17 are grafts of the phase shift frequency and amplitude of another embodiment of the system illustrated in FIG. 10;

FIG. 18 is a detailed circuit diagram of another embodiment of the tremulant system in accordance with the present invention;

FIG. 19 is a schematic circuit diagram of still another tremulant system in accordance with the present invention which permits trimming of the exact degree of phase shift and precise synchronization of the original signal with the phase-shifted signal; and

FIG. 20 is a schematic circuit diagram of still another tremulant system in accordance with the present invention.

Referring to FIG. 1, the electrical output signals from an organ 10 are fed to the tremulant modulation system 12 which is constructed in accordance with the present invention. If desired, the modulation system 12 may be packaged as a very small volume system and disposed inside the organ 10. The system 12 operates upon the audiofrequency signals from the organ 10 in a manner to be later described and provides a modulated output signal to drive the speaker system 14. Both vibrato and tremolo effects may be introduced by the system 12 according to a preselected periodic modulation pattern, or alternatively, exterior controls on the system 12 may be operated by the musician in order to produce varied musical

effects as desired. The modulation system **12** is capable of driving the speaker system **14** to closely simulate the operation of a rotating speaker of the Leslie type.

FIG. **2** illustrates another configuration of the present invention wherein an electric guitar **16** and another musical instrument such as an organ **18** are connected to the input of a preamplifier **20**. It will be understood that the present invention is not limited to use with any particular type of musical instrument, but that the illustrated instruments are utilized for disclosure purposes only. The output of the preamplifier **20** is fed to a tremulant system **22** according to the invention and is also fed to the input of a nontremulant amplifying system **24**. The tremulant system **22** may be operated according to a preselected periodic modulation cycle, or may be selectively varied to produce different tremulant effects by the use of suitable controls operated by the musician. The outputs of the tremulant system **22** and the nontremulant system **24** are combined and fed to an amplifying system **26** which drives a speaker system **28**.

FIG. **3** is a schematic diagram of an embodiment of the basic tremulant circuit according to the invention. The input audiofrequency signal is represented by the signal source **30**, it being understood that this signal may be provided by any one of a number of different musical instruments. The audiofrequency signal is fed through a transformer **32** which has a center-tapped secondary grounded via a lead **34**. One terminal of the secondary of the transformer **32** is connected to a variable resistance **36**. A capacitor **38** is connected between the resistor **36** and circuit ground to form a low pass filter network. The output from the low pass filter network is fed via a resistance **40** to the output of the circuit.

The other terminal of the secondary of the transformer **32** is connected to a capacitor **42**, one terminal of which is connected through a variable resistance **44** to circuit ground. Capacitor **42** and variable resistance **44** comprise a high pass filter, the output of which is fed via a resistance **46** to the output of the circuit. In the preferred embodiment, the variable resistances **36** and **44** are photosensitive and are preferably, but not necessarily, of the cadmium sulfide or cadmium selenide type. A light source **48** is driven by an electrical generator **50** in a preselected manner in order to provide a variable source of illumination to the photosensitive variable resistances **36** and **44**. The variable illumination impinged upon the resistances **36** and **44** varies the frequency responses of the high pass and low pass filters to induce tonal variations in the audio frequency signal in the manner to be subsequently described.

FIG. **4** diagrammatically illustrates the operation of the present tremulant circuit. The frequency response of the low pass filter comprising resistor **36** and capacitor **38** is represented by the curve **52**. The frequency response of the high pass filter comprising capacitor **42** and resistor **44** is represented by the waveform **54**. The waveforms **52** and **54** intersect at a crossover point **56**. In this instance, the crossover point is at the 50-percent level, or midway between the high and low frequency responses of each filter bandpass.

By varying both of the variable resistors **36** and **44** with the same light source **48**, the frequency response of one of the filters may be concurrently increased while the frequency response of the other filter is decreased, and vice versa. Thus, variation of the resistances in both the filters varies the rollover point **58** of the waveform **52** between points **58***a* and **58***b*, while the rollover point **60** of the waveform **54** is concurrently varied between points **60***a* and **60***b*. This variance of the rollover points of the output waveforms from the filters thus varies the position of the crossover point between the points **56***a* and **56***b*.

As an example of the operation of the tremulant circuit, assume that the value of the resistances **36** and **44** is such that the crossover point of the waveforms **52** and **54** is at **56***a*. All frequencies lower than the frequency at point **56***a* will be 180° out of phase with the frequencies higher than the frequency at point **56***a*. Assuming that the light impinged upon the resistances **36** and **44** is changed such that the crossover point is moved to **56**b, successively higher frequencies, are reversed in phase by 180° during the movement of the crossover point, thus producing a tremulant effect.

Interesting effects can be obtained by mixing the unmodulated signal at the input of the tremulant circuit with the modulated signal at the output of the circuit. The relative amplitudes of the unmodulated and modulated signals can be varied as desired by suitable variable networks, as will hereafter be described in detail.

The crossover point **56** of the waveforms **52** and **54** need not be at the 50-percent level. As shown in FIG. **5**, the crossover point **56** may be considerably below the 50-percent level to provide an unusual amplitude modulation of the output audiofrequency signal when the crossover points are varied between **56***a* and **56***b* in the manner previously described. It will also be understood that crossover points at substantially greater levels than the 50-percent level could also a be advantageously utilized. The circuit has been described as having resistances which vary linearly to maintain the crossover point at generally a constant amplitude during variation of the frequency of the crossover point. However, it will be understood that in some instances, it may be desirable to vary the magnitude of one or more of the variable resistances in a nonlinear manner, thus providing a fluctuating amplitude to the changing crossover point to induce unusual and unique musical effects.

In order to further illustrate the operation of the tremulant circuit shown in FIG. **3**, assume as a first case that the values of the variable resistances **36** and **44** are much greater than the values of the capacitive reactance of the capacitors **38** and **42** for an applied sine wave having a reference frequency. For simplicity, the values of the resistors are assumed to be equal and the values of the capacitors are also assumed equal. The low pass filter comprising the resistance **36** and the capacitor **38** will thus attenuate the portion of the input sine wave such that the amplitude of the waveform applied to the resistor **40** is negligible. Conversely, the high pass filter comprised of the capacitor **42** and the resistance **44** will not greatly affect the portion of the sine wave fed therethrough, and thus the waveform applied to the resistor **46** will be almost identical to the sine wave applied to the high pass filter. The resultant output signal from the tremulant circuit will thus have phase characteristics similar to the waveform applied to the resistor **46** from the high pass filter and will have an amplitude of approximately one-half the input sine wave. The resultant output signal will also be 180° out of phase with the portion of the input sine wave applied to the low pass filter.

Now assuming as a second case that the values of the resistances **34** and **44** are much less than the value of the capacitive reactance of capacitors **38** and **42** at a reference frequency, the waveform applied to resistor **40** will not be greatly attenuated and will thus be almost identical to the portion of the input signal applied to the low pass filter comprising the resistor **36** and the capacitor **38**. However, the high pass filter comprising capacitor **42** and resistor **44** will substantially attenuate the portion of the input signal fed therethrough. Thus, the resultant output of the circuit will have phase characteristics similar to the signal applied to the resistor **40** from the low pass filter and will have an amplitude of approximately one-half the input signal applied from the source **30**. It should be noted that the resultant output in this case is 180° out of phase with the resultant output obtained in the first case.

As the magnitudes of the variable resistances approach the capacitive reactances of the capacitors **38** and **42**, the resultant output of the circuit will approach the amplitude of the resultant output provided by either the first or second case, but will be phase shifted 90° with respect to either of the resultant outputs of the two cases. It should then apparent that the 180° phase shift from the first case to the second case will take place smoothly upon a linear variation of the magnitudes of the resistances.

Although the operation of the tremulant circuit shown in FIG. 3 has been described with respect to an input signal having only a single frequency, it will be understood that the circuit operates on complex signals having a number of frequencies in the same manner. However, with such complex signals, each different frequency contained therein will be sequentially operated upon as the relative magnitudes of the resistances are varied.

Use of the present tremulant circuit with complex audio frequency signals causes apparent change of the frequencies of the signals to create a heterodyne change in the harmonic structure of the signals. Operation of the circuit gives the acoustical illusion of multipath effects and acoustical depth which have formerly been possible only with the use of mechanical rotating-type speakers.

It is often desirable to connect a plurality of the tremulant circuits shown in FIG. 3 in series. FIG. 6 illustrates a first tremulant circuit **70** according to the invention which is connected in series with a second like tremulant circuit **72**. As the tremulant circuits **70** and **72** are identical, like numbers will be utilized for like and corresponding parts therein. Tremulant circuits **70** and **72** are similar to the basic circuit shown in FIG. **3**, with the addition of amplifying circuitry. The input audiofrequency signal is fed to a transformer **74**, with one terminal of the center-tapped transformer secondary being connected to a variable resistance **76**. The output of the resistance **76** is fed to a grounded capacitor **78** and to a resistor **80**. The lower terminal of the transformer secondary is connected to a capacitor **82** connected in series with a grounded variable resistor **84**. The common terminals of the capacitor **82** and resistor **84** are connected to a resistor **86**.

The common terminal of resistors **80** and **86** are connected through a feedthrough capacitor **88** to the base of a transistor **90**. Resistors **92–98** are connected in a conventional amplifying configuration to the transistor **90**. Capacitor **100** is connected between the emitter of the transistor **90** and ground. The output of the transistor **90** is fed from the collector thereof through capacitor **102** to the next circuit stage.

Operation of each of the tremulant circuits **70** and **72** is similar to the operation of the circuit shown in FIG. **3**, with amplification being provided to the output thereof. Each of the tremulant circuits **70** and **72** provides a frequency shift of 180° to input signals as the tremulant circuits are varied through one cycle by suitable variable light sources (not shown). The series connection of the two circuits **70** and **72** thus causes a phase shift of 360° of the input signal as the frequency responses of the filter networks therein are varied through a cycle. Similarly, three series connected tremulant circuits will provide a 540° phase shift.

The use of plurality of series connected tremulant circuits increases the slope of the frequency responses of the circuits in the area of the crossover point. For instance, whereas one tremulant circuit may be provided with a frequency response slope from the rollover point of about 6 db per octave, the slope of the frequency response of three series-connected tremulant circuits would be about 18 db per octave. The steeper slope of the frequency response in the area of the crossover point provides a much sharper phase reversal upon variance of the tremulant circuits, thereby emphasizing the tremulant effect provided by the system.

Although the use of photosensitive resistors and a variable light source have been illustrated for variance of the filters of the tremulant circuits, any other suitable variable components may be used in the invention. For instance, a mechanically variable capacitance could be utilized in place of a variable resistance. Alternatively, a filter circuit utilizing a variable inductance such as a saturable reactor could be utilized. Further, the variable resistances could be mechanically varied potentiometers.

FIG. 7 illustrates an embodiment of a circuit which has been found advantageous in driving a variable light source for control of photosensitive elements in the tremulant circuits. A DC signal is applied to the circuit via a resistance **110** to directly determine the frequency of the variable illumination of a lamp. The level of the DC signal applied via the resistor **110** may be varied by manually operable controls (not shown) located on or near the musical instrument. A first positive reference voltage V_1 is applied to a potentiometer **112**, while a second reference positive voltage V_2 is applied to a potentiometer **114**. The cathode of a diode **116** is connected to the adjustable arm of the potentiometer **112**, while the anode of the diode **118** is connected to the adjustable arm of the potentiometer **114**.

Diodes **116** and **118** are commonly connected to a terminal **119** which is connected to a grounded capacitor **120**. Terminal **119** is connected via resistor **122** and a variable resistor **124** to a unijunction transistor **126** which serves as the time base element of the circuit. Bias voltage is fed via resistor **128** to the transistor **126**. A capacitor **130** is connected between ground and the input of the transistor **126**. The output of the transistor **126** is applied to one terminal of a grounded resistor **132** and also to the emitter of a transistor **134**.

Transistor **134** is connected in a multivibrator configuration to a transistor **136**. R-C networks **138** and **140** are connected between transistors **134** and **136** in the conventional multivibrator configuration. Bias voltage is applied to the transistor **134** and **136** via resistors **142** and **144**, respectively. The output of the multivibrator is fed via a resistor **146** to the base of a transistor **148**. A transistor **150** is connected across the output of the transistor **148**, the emitter of the transistor **150** being connected to a grounded lamp **152**. A resistor **154** is connected between the base of the transistor **150** and circuit ground. A capacitor **156** is connected between the base of the transistor **148** and ground, with a capacitor **158** being connected across capacitor **156** in series with photosensitive variable resistor **160**.

The base of a transistor **162** is connected to terminal **119**. The emitter of transistor **162** is connected to a grounded resistor **164** and also to the base of a transistor **166**. The collector of transistor **166** is connected to a grounded resistor **168** and also to the base of a transistor **170**. The collector of transistor **170** is connected to a grounded lamp **172**.

In operation of the circuit shown in FIG. **7**, the unijunction transistor **126** is fired when the voltage applied at terminal **119** reaches a preselected level. The output signal of the transistor **126** is a spike pulse which triggers the bistable multivibrator comprising transistors **134** and **136**. The output of the multivibrator is fed via resistor **146** to provide a square wave having a frequency of one-half the frequency of the time base output from transistor **126**. That is, for each two spike pulses received from the transistor **126**, one square wave is generated by the multivibrator circuit.

The square waves from the multivibrator are fed to an R-C integrator circuit comprising resistor **146** and capacitances **156** and **158**. The time constant of the R-C integrator circuit is controlled by the magnitude of the voltage to terminal **119**. This voltage controls the operation of transistors **162**, **166** and **170**. The output of the transistor **170** controls the illumination of the lamp **172**, which in turn controls the magnitude of the resistance **160**.

By proper selection of the component values of the circuit, the amplitude and waveshape of the signal applied to the driver transistors **148** and **150** may be substantially constant over a relatively broad range of operating frequencies. The transistors **148** and **150** drive the lamp **152** with a generally triangular response due to the R-C integrator circuit. The lamp **152** also provides an integration to the resulting illumination due to the response factors of the Wolfram lamp filament therein. Thus, the resulting illumination applied from the lamp **152** is a generally sinusoidal waveform. The period of the generator shown in FIG. **7** may be variable from about 1 cycle per second to about 15 cycles per second to provide various desired effects.

An important feature of the invention is that the rate of change of the voltage applied via the resistor **110** may be selectively varied to dynamically simulate the starting and

stopping characteristics of a mechanical rotating speaker. Further, by adjustment of the potentiometers **112** and **114**, the maximum and the minimum voltage that may be developed at the terminal **119** is limited to simulate the operation of a two-speed mechanical rotating speaker.

FIG. **8** illustrates another embodiment of a circuit for driving a lamp to vary photosensitive elements in the tremulant circuit of the invention. A positive reference voltage is applied to the cathode of a Zener diode **180** and to the anode of a Zener diode **182**. A positive bias voltage B_1 is applied to the series connected Zener diodes via a resistance **184**. Bias voltage is also applied through a resistor **186** to a unijunction transistor **188**. The output of the transistor **188** is fed to the emitters of transistors **190** and **192** which are connected together in a multivibrator configuration. R-C networks **194** and **196** are connected between the transistors **190** and **192** in the conventional bistable multivibrator configuration.

The output of the multivibrator is applied via a variable resistance **198** to a grounded capacitor **200** and to a capacitor **202**. A grounded photosensitive variable resistor **204** is connected in series with capacitor **202**. The output from the multivibrator fed via resistor **198** is also fed to the base of a power transistor **206** which is connected in a ganged configuration with power transistors **208** and **210**. The emitter of the transistor **210** is connected to a lamp **212** for energization thereof.

The input of the unijunction transistor **188** is connected via a lead **214** to a variable resistance **216** which is connected in series with a fixed resistance **218**. A capacitor **220** is connected between circuit ground and the resistance **218**. A resistor **222** is connected to one terminal of the capacitor **220**, with a Zener diode **224** connected in series with the resistor **222** and the emitter of a transistor **226**. The base of the transistor **226** is connected to a diode **228**, the cathode of which is connected to a suitable switch **230**. A positive bias voltage is applied via lead **232** to the transistor **226**.

A terminal of the capacitor **220** is also connected to the cathode of a Zener diode **234** and to the base of a transistor **236**. The anode of the diode **234** is connected to the variable arm of a potentiometer **238** connected between a supply of reference voltage and ground. Transistor **236** is connected in a ganged configuration with power transistors **240** and **242**. The emitter of transistor **242** drives a lamp **244**.

In operation, the circuitry of FIG. **8** operates in a similar manner to the circuit shown in FIG. **7**. The minimum speed desired for the circuit is set by adjustment of the potentiometer **238**. The frequency of operation of the circuit is determined by the voltage applied to the input of the unijunction transistor **188**. Transistor **188** generates a stream of spiked pulses which drives the multivibrator comprising transistors **190** and **192**. The square wave output of the multivibrator is fed into the integrator circuit comprising resistance **198** and capacitors **200** and **202**. The resulting integrated waveform drives the power resistors **206–210** to selectively energize the lamp **212**.

The variable resistance **204** is varied according to the illumination of the lamp **244**, which in turn is controlled by the operation of the transistors **236, 240** and **242**. The switch **230** may be manually operated in order to selectively control the time constant of the integrator network as desired.

Whereas circuits have been disclosed for providing a generally triangular or sinusoidal energization wave to control a light source, other waveform shapes such as trapezoidal or the like may also be advantageously utilized. The particular shape of the waveform utilized to drive the light source for variance of the filters in the tremulant circuits will be chosen according to the desired tonal qualities.

FIG. **9** shows a preferred embodiment of a system utilizing two channels of series connected tremulant circuits according to the invention. The output from a musical instrument is fed into the system via a capacitor **250** to the base of a transistor **252**. The emitter of the transistor **252** is connected to a first filter network comprising capacitors **254** and resistors **256** designed to filter a selected band of low audiofrequencies. The emitter of the transistor **252** is also connected to a second filter network comprising resistors **258** and capacitors **260** having component values designed to filter a selected band of relatively high audiofrequencies.

For instance, the filter network comprising capacitors **254** and resistors **256** may filter frequencies up to about 800 cycles per second, while the filter network comprising resistors **258** and capacitors **260** may filter frequencies above 800 cycles per second. In some instances, a fixed shunt resistance may be desirably connected to the circuit to eliminate the modulation of frequencies under a predetermined frequency, such as about 130 cycles per second, in order to more accurately simulate the operation of a mechanical rotating speaker of the Leslie type.

The output from the high pass filter network is fed into four series connected, identical tremulant circuits **262, 264, 266** and **268**. Only one of the tremulant circuits is illustrated for simplicity, with each of the circuits comprising a feedthrough capacitor **270** connected to the base of a transistor **272**. Conventional bias resistors are connected between transistor **272** and a source of bias voltage.

The collector of the transistor **272** is connected to the base of a transistor **274**, while the emitter of the transistor **272** is connected to the base of a transistor **276**. The signals fed to the bases of transistor **274** and **276** will thus have frequencies above the preselected cutoff frequency of the filter and will also have phases 180° out of phase. The emitter of the transistor **274** is fed to a high pass filter comprising capacitor **278** and variable resistor **280**. The signal appearing at the emitter of the transistor **276** is fed through a capacitor **282** and a grounded resistor **284** to a variable resistor **286**. A capacitor **288** in connected between ground and one terminal of the variable resistor **286** to provide a low pass filter.

The common terminal of the capacitor **278** and the resistor **280** is connected to a resistor **290**, while the common terminal of the resistor **286** and the capacitor **280** is connected to a resistor **292**. The combined outputs of the two filters are fed through a capacitor **294** to the base of an amplifying transistor **296**. The collector of the transistor **296** is connected to the input of the next series connected tremulant circuit **264**.

A variable light source **298** is driven by a signal generator **300**, which may preferably comprise the circuit illustrated in FIG. **8**. The light from the light source **298** impinges directly upon the variable resistances in each of the tremulant circuits **262–268**. The output from the series connected tremulant circuits is fed through a resistor **302** and a feedthrough capacitor **304** to the base of an amplifying transistor **306**. The amplified output is fed through a capacitor **308** to the base of a transistor **310**. The emitter of the transistor **310** generates the modulated output signal provided by the system.

The signal passed through the low pass filter comprising resistor **258** and capacitors **260** is fed to three series connected identical tremulant circuits **320, 322**, and **324**. Each of the tremulant circuits comprises a feedthrough capacitor **326** which supplies the filtered audiofrequency signal to the input of the transistor **328**. The collector of transistor **328** is connected to a capacitor **330** and a variable resistor **332** for filtering a selected low frequency band. The emitter of the transistor **328** is fed through a resistor **334** connected to circuit ground and also to a capacitor **336**. A resistor **338** is connected between ground and a capacitor **336** and is also connected to one terminal of a variable resistor **340** according to the invention.

A capacitor **342** is connected to the other terminal of the resistor **340** and also to a terminal of a resistor **344**. The common terminals of the capacitor **330** and the variable resistor **332** are connected to a resistor **346**. The common terminals of resistors **344** and **346** are connected through a capacitor **348** to the base of an amplifying transistor **350**. The collector of the transistor **350** is applied to the next tremulant circuit **322**. A lamp **352** is controlled by a signal generator system **354**, which in the preferred embodiment is similar to the circuit

shown in FIG. 8. The output of the third tremulant circuit 324 is fed via a resistor 356 through the capacitor 304 to the output transistors 306 and 310. It is important to note that the signal generators 300 and 354 are preferably operated at different rates in order to produce unique musical effects which are pleasing to the ear.

A circuit for providing spring-type reverberation to the modulated audio frequency signal is connected across the parallel channels shown in FIG. 9. The reverberation circuit comprises a capacitor 360 which supplies the audiofrequency signal to the base of a transistor 362. A capacitor 364 is connected across the transistor 362. The emitter of transistor 362 is applied to the base of a transistor 366. The collector of the transistor 366 is fed through an R-C network 368 to the base of a transistor 370. The cathode of a diode 371 is connected between the network 368 to circuit ground. The collector of the transistor 366 is applied via a resistor 372 to the collector of the transistor 370. The collector of the transistor 370 is fed through a capacitor 374 to the primary of a loosely coupled transformer 376.

The secondary of the transformer 376 is fed via a capacitor 378 to the base of a transistor 380. The collector of the transistor 380 is fed via a capacitor 382 to the base of a transistor 384, the collector of which is fed via capacitor 386 to a potentiometer 388. The movable arm 390 of the potentiometer is fed through a capacitor 392 and a resistance 394 to the base of the transistor 306.

In the operation of the circuit shown in FIG. 9, high frequencies of the audiofrequency signal are passed through the series connected tremulant circuits 262–268, whereupon the frequency responses of the parallel filters in each of the tremulant circuits are varied according to the output of the lamp 298. The crossover frequencies of the filters in each of the tremulant circuits are concurrently increased and decreased as previously described to induce a tremulant effect into the selected high frequency band of the input signal. The series connection of a plurality of tremulant circuits provides a relatively high slope to the filter frequency responses in the area of the crossover frequency, thereby imparting relatively sharp changes of phase and amplitude to the modulated signal.

A similar tremulant effect is induced into the lower frequencies of the input signal which are fed through the three series connected tremulant circuits 320–324. When the outputs from the high and low frequency channels are combined and fed through the capacitor 304 to the amplifying output circuitry, a very unusual and pleasing musical effect is obtained. The provision of the reverberation circuitry induces additional unusual tonal qualities to the output signal. The relative rates of the signal generators 300 and 354 may be selectively operated by the musician to very accurately simulate the use of mechanical rotating Leslie-type speakers. The system shown in FIG. 9 is not limited to use with any particular musical instrument, but is unilaterally compatible with almost any source of audiofrequency signal.

As previously mentioned, it is often desirable to mix the tremulant output with the nontremulant output. Such a system is indicated generally by the reference numeral 500 in FIG. 10. The output of a music source 502 is coupled to the input of the phase shift network 506. The output of the phase shift network 506 is summed with the output from the music source 502 through a summing network comprised of resistors 508 and 510, and is then applied to an audio generator system 512. The capacitors 504 and 514 provide DC isolation from the phase shift network 506.

The music source 502 may be any means for producing electrical signals representative of a musical sound, such as an electric organ, electric guitar, microphone pickup for voice, record playing system, or any preamplifier system for musical sounds. The audio generator 512 includes the necessary amplifier system for musical sounds. The audio generator 512 includes the necessary amplifiers to drive a speaker system as well as the speaker system for producing musical sounds from the electrical signals representative of the musical sound.

The phase shift network 506 preferably produces at least 720° of phase shift. Any phase shift network may be used for this purpose so long as the amplitude of the signal remains substantially constant as the phase is shifted. For example, stages 262, 264, 266 and 268 of FIG. 9 may be used to provide substantially 720° of phase shift without amplitude attenuation if the upper and lower fillers of each stage are properly matched. The resistors 508 and 510 in the summation network are preferably chosen so that the output of the phase shift network 506 and the output of the music source 502 are mixed in approximately equal proportions for application to the audio generator 512. For commercial applications, it is desirable to make the mixing ratio variable within a relatively narrow range and within the control of the musician so that he can vary the depth of amplitude modulation as hereafter described.

The operation of the system 500 is illustrated in FIGS. 12–14. FIG. 12 illustrates the phase shift produced by the phase shift network 506 for each scan cycle of the lamp 298. The zero point of the cycle has been selected as a point of maximum illumination, and the 180° point of the cycle representing minimum illumination. The light dependent resistors vary in resistance inversely with illumination. The curve 520 represents the phase shift of a single frequency which may be considered a wide-range musical note. As a result of the cyclic phase shift f from 0° to a lag of 720°, the frequency is modulated as represented by the curve 522 in FIG. 13. By mixing the output from the phase shift network 506 with the original signal from the music source 502 in approximately equal ratios, the amplitude is modulated as represented by the curve in FIG. 14. The combination of the frequency modulation as represented in FIG. 13 and the amplitude modulation as illustrated in 14 produces a sound substantially identical to the sound of a rotating speaker such as represented in the schematic view of FIG. 10.

Referring to FIG. 10, it will be noted that when the speaker is in the position shown in said outline and designated "0°," a person positioned in front of the speaker would hear a maximum amplitude signal with no apparent change in frequency. When the speaker reaches the 90° position, the amplitude becomes nulled because the signal emanating from the rear end of the speaker is 180° out of phase from the signal emanating from the front of the speaker and of approximately equal amplitude, thus theoretically cancelling along an interface disposed generally 90° to the axis of the speaker. When the speaker reaches the 180° position, substantially full amplitude is again received because of the signal emanating from the rear of the speaker, and the listener is unable to detect the 180° phase difference in the signal. When the speaker reaches 270°, a null once again occurs.

If the speaker is located in a square cabinet, a large number of amplitude nulls occur at various positions of the speaker, depending also upon the position of the listener. However, whenever the speaker is pointing either directly toward or directly away from the listener, the direct sound tends to override the cancellation caused by out-of-phase reflections. It has generally been known that as the speaker rotates, each frequency will decrease to a minimum point at the 90° position, will return to the nominal frequency at the 180° position, and will change to a maximum at the 270° position, and will change to a maximum at the 270° position as a result of the Doppler effect.

Now comparing the sound produced by the rotating speaker 525 to the sound depicted by the curves in FIGS. 12–14, it will be noted that the frequency of the sound produced by the system 500 decreases to a minimum at the 90° position because that is the position of greatest rate of phase shift, passes back through the norm represented by the dotted line 523 at the 180° position, reaches a maximum at the 270° position, and again returns to the norm at the 0° position. More importantly, because of phase cancellation in the summing network 508–570, the amplitude (FIG. 14) reaches a null at approximately the 75° position as a result of the 180° phase

difference in the two signals, reaches a maximum at the 90° point as a result of the reinforcement at the 360° phase shift, and again is nulled at about the 105° position as a result of the out-of-phase cancellation at a phase shift of 720°, which is an in-phase condition. The same double null condition is produced in the vicinity of the 270° position.

In reality, the double null resulting from 720° of phase shifts is more pleasant to the ear and more closely simulates the effect of a rotating speaker contained in a cabinet than does a single null which would be produced by 360° of shift, even when the total frequency shift is much greater than 360° using a circuit hereafter described which produces the multiple reflections and cancellation patterns. It should also be noted that lines **520**, **522** and **524** represent but a single frequency. The other frequencies in the audio range will be shifted at different points in the scan cycle as represented by the dotted lines **520H** for the high frequencies and **520L** for the low frequencies. Thus the null points actually occur at points ranging between positions **524H** and **524L** in FIG. **14**, depending upon the frequency content of the musical sounds. As a result, the ear cannot detect the two distinct null positions, but instead detects a dynamically changing amplitude pattern that very closely simulates a rotating speaker in a cabinet.

From FIG. **12**, **13**, and **14** it will be noted that as long as the phase shift $\phi=2\pi n$ where n is an interger, the shape of the frequency and amplitude curves **522** and **524** will remain substantially the same except that the number of nulls at the 90° and 207° positions will be equal to n. Due to the sinusodial slope of the phase shift curve **220**, however, these nulls remain closely bunched at a 90° and 270° with relatively broad full amplitude lobes **524A** at the 0° and 180° positions. In general, a greater number of nulls around the 90° and 270° positions enhances the effect of creating the sound of a rotating speaker within a square cabinet. Phase shifts of about 1,080° and about 1,440° produce particularly pleasing results.

The effect of the increasing the total phase shift in each cycle is to increase the extent modulation excursions of the frequency. Since the rotational rate, i.e., the scan rate of the light-dependent resistors, remains constant, the overall effect is a simulation of rotating a speaker around a circle of larger diameter at the same rate of rotation.

As previously mentioned, it is desirable for the resistors **508** and **510** to be selected so as to sum to output from the phase shift network **506** and the music source **502** in approximately a 1:1 ratio. By referring to FIG. **14**, it will be noted that such a ratio produces a theoretical null on each side of the 90° and 270° positions of the speaker. As the proportion of the output from the music score **502** is reduced, the amplitude modulation is softened, which is desirable for some types of music. For this reason, it may be desirable to provide an adjustable mixing network to permit the musician to adjust the summation ratio. However, as the output from the music source **202** is reduced below half that from the network **506**, the effect of a rotating speaker is substantially lost, with the effect being just straight vibrato.

Quite a different effect occurs as the proportion of signal from the music source **502** is increased above that portion supplied by the phase shift network **506**. By the time the proportions from the music source **502** reaches about 1.5 times that from the phase shift **506**, the nonvibrato sound begins to dominate and the effect of a rotating speaker is greatly diminished. By the time the signal from the music source **502** is twice that from the phase shift network **506**, the effect of a rotating tremulant effect is produced. As the proportion of nonshifted signal increases, the effect becomes similar to the conventional chorus vibrato presently available on some domestic organs.

FIGS. **15**, **16** and **17** illustrate the frequency modulation which are produced when the phase shift network **56** produces a phase shift $\phi=2\pi n+1$. In FIG. **14**, a phase shift of −540° represented by line **526**. This produces an amplitude modulation represented by the line **528** in FIG. **16** that is of the same phase heretofore described, but has lower excursions of apparent frequency. However, the amplitude as represented by curve **530** is substantially different due to the fact that when the scan cycle is equivalent to the 180° position of the speaker, the signal from the music source **502** is 180° out of phase from the output of the phase shift network **506**, thus producing a relatively long null during every other half cycle. This contradicts the condition of substantially maximum amplitude produced by a speaker having equal efficiency toward both the front and rear. It will also be noted that the nulls at the 90° and 270° speaker positions are shifted toward the 180° position.

In the lower degrees of phase shift, for example 540°, this condition is not as pleasant to the ear as a rotating speaker. However, as the degree of phase shift is increased, this undesirable effect seems to diminish.

This may be due to the fact that the null at the 180° position is narrowed and thus lasts for a shorter period of time, because the test circuit did not produce the exact degree of phase shift required to produce a noticable null.

An alternative embodiment of the system of the present invention is indicated by the reference numerals **540** in FIG. **20**. System **540** includes two of the phase shift networks of **506** of FIG. **10**, with the associated summation networks comprised of resistors **508** and **510**, connected in series. Corresponding components are therefore designated by the same reference characters in FIG. **20** as in FIG. **10**. The effect of the circuit **540** is to provide a large degree of phase shift without producing a large number of nulls at the 90° positions of rotation. Thus, if each of the phase shift networks **506** produces only 360° of the phase shift, for example, only a single null positioned directly at the 90° and 270° positions will be produced. Similarly if two circuits having 720° of phase shift are connected in series, a total of 1,440° of phase shift will be produced with only two nulls at the 90° and 270° positions.

A preferred embodiment of the phase shifted network is indicated at generally by the reference numerals **550** in FIG. **18**. The phase shift network **550** is comprised of four identical stages in which corresponding components are designed by the same reference numerals. For example, each stage is comprised of a transistor **552** with the appropriate collector, emitter and base biassing network comprised of resistors **554**, **556**, **558** and **560**. A capacitor **562** couples the collector of the transistor **552** to an output **564**. A light-dependent resistor LDR **566** couples the emitter to the output **564**. The output **564** is coupled by a capacitor **568** to the input of the next stage. Capacitors **570** and **572** provide DC isolation for the phase shift network.

The resistance of light dependent resistors **566** varies with illumination from a low value to a high value such that each stage produces a phase shift which varies from approximately 0° when the LDR is fully illuminated to approximately 180° when the LDR is dark. The signal from the music source is input at **574** and is summed with the output from the last stage of the phase shift network by a summation resistor **576**, as heretofore described. The center tap of the resistor **576** is preferably adjustable so that the musician may vary the ratio in which the two signals are mixed from a ratio of about 2:1 to a ratio of about 1:2. When using four stages as illustrated, the total phase shift is approximately 720°, although the phase shift does not reach 0° or does it reach a full 720° due to the inefficiency of the individual stages.

Referring now to FIG. **20**, another circuit in accordance with the present invention is indicated generally by the reference numeral **600**. The system **600** includes an input **602** for receiving a signal from a music source and an output **604** for connection to an audio generator as heretofore described. The phase shift circuit **600** has a plurality of identical stages S_f–S_x which, it will be noted, are identical to the stages of the phase shift network **550**. However, the last stage **606** includes a pair of variable resistors **608** and **610**. Resistor **608** is connected in series with the light-dependent resistor **612** and resistor **610** is connected in parallel. This resistor circuit provides a means for adjusting the total phase shift of the network

to a selected value, within a limited range. For example, the combined resistance of the parallel branches of resistors **608** and **610** determine the minimum phase shift of the stages when the LDR **612** is fully illuminated and therefore at a minimum resistance value. The value of resistor **610** determines the maximum phase shift of the stage when the LDR is dark. It will be noted that the phase shift produced by stage **606** is taken from the linear part of the phase shift curve, and is therefore also useful in shaping the phase shift curve **120** of FIG. **12**, for example, as will be presently described.

The signal at the input **602** is also passed through a phase shift stage **614** which has a variable resistor **616** in place of an LDR. The variable resistor **616** may be adjusted so as to synchronize the signal from the output of the phase shift stage **606** with the signal from the music source applied to input **602**. Resistors **618** and **620** provide a summation in network as heretofore described for summing the signal from stages **606** and the signal from stage **614**. Capacitors **622** and **624** provide DC isolation. Thus the adjustable stages **606** and **614** provide a means for precisely synchronizing the output of stage **614** with the output of stage **614** at the 0° position, i.e., when the LDR's are fully illuminated, by adjusting resistor **616**. Then the total phase shift network can be adjusted by resistors **608** and **610**, so that the phase relationship between the two signals at the 180° position, i.e., when the LDR's are dark.

It will also be noted that the phase shift stage **606** can be used to shape the phase shift curve **520**, for example, of FIG. **12**. Since the maximum and minimum resistance of the network between the emitter and the output of the stage are fixed, only the linear portion of the phase shift curve is used. By using the plurality of such phase shifts, the slope of the curve **520** in the vicinity of the 90° and 270° position speaker may be increased substantially without effecting the slope of the curve in the vicinity of the 0° and 180° positions. The shape of the curve **520** may also be adjusted by the manner in which the light dependent resistors are varied.

As previously mentioned, the shape of the amplitude curve **524** is determined by the relative phase relationship of the signals applied to the summation network resistors **618** and **620**, for example. Thus by making the phase shift at the 180° position something other than an in-phase condition, the amplitude of the large lobe at the 180° position can be reduced as desired. For example, if a speaker to be simulated is slightly less efficient to the rear of the speaker than in front of the speaker, the total phase shift may be made 780°, for example, and thereby produce some attenuation at the 180° position. It will be noted that such an increase in phase shift does not materially change the positions of the nulls at the 90° and 270° positions. Similarly, the total phase shift be made slightly less than 720°.

Another effect can be produced by substituting a phase shift stage like stage **606** in FIG. **20** for phase shift stage **614**, and providing a second light which is cycled at a slower rate for illuminating the LDR. Such a system provides a means for continually shifting the positions of the amplitude lobes on the amplitude curves of FIG. **14** relative to the apparent position of the speaker. This simulates the rotation of a square cabinet about the rotating speaker at a slower speed, and produces an unusual and pleasing musical effect for the more modern types of music.

Whereas the present invention has been described with respect to several specific embodiments thereof, it will be understood that various modifications and changes will be suggested to one skilled in the art, and it is intended to encompass these changes and modifications as fall within the true scope of the appended claims.

What is claimed is:

1. A system for modulating a signal comprising:

a. a plurality of parallel-connected filter means each discriminating against different frequencies,

b. means for applying electrical signals representative of said signal with different phases to said filter means,

c. means for varying the frequency response of at least one of said filter means, and

d. means for recombining the outputs of said filter means with the signal being modulated.

2. The system of claim **1** wherein one of said filter means discriminates against frequencies below a preselected frequency and another of said filter means discriminates against frequencies above said preselected frequency.

3. The system of claim **2** wherein the electrical signal applied to said one filter means is 180° out of phase with the electrical signal applied to said another filter means.

4. The system of claim **1** wherein the frequency response of a pair of said filter means is varied to modulate both the frequency and the amplitude of said signal.

5. A modulation system for audiofrequency signals comprising:

a. first filter means for discriminating against frequencies below a first rollover audiofrequency,

b. second filter means connected in parallel with said first filter means and discriminating against frequencies above a second rollover audiofrequency such that the cutoff frequency responses of said first and second filter means overlap at a crossover frequency,

c. means for applying audiofrequency signals to said first and second filter means in phase opposition,

d. means for cyclically varying said crossover frequency by increasing the rollover frequency of one of said filter means while concurrently decreasing the rollover frequency of the other of said filter means, and

e. means for combining the outputs of said first and second filter means.

6. The system of claim **5** and further comprising means for selectively varying the frequency of the cyclical variations in the frequency response of said first and second filter means.

7. The system of claim **5** wherein each said filter means comprises:

a series connected capacitor and resistor tuned to discriminate against preselected frequency bands, said resistor being variable to change the preselected frequency bands.

8. A system for modulating the audiofrequency output signal of a musical instrument comprising:

a. a first filter network for discriminating against low frequencies connected to receive said output signal,

b. a second filter network for discriminating against high frequencies connected in parallel to said first filter network,

c. first and second modulation networks each connected to one of said filter networks, each modulation network including parallel high and low bandpass filters for operating on signals of opposed phases,

d. means for varying the frequency responses of said modulation networks, and

e. means for combining the outputs of said modulation networks.

9. The system of claim **8** wherein each of said modulation networks includes a tremulant circuit comprising:

a. means for generating two signals in phase opposition each representative of said audiofrequency output signal,

b. first filter means for discriminating against frequencies below a first rollover frequency connected to receive one of said two signals,

c. second filter means connected in parallel with said first filter means for receiving the other of said two signals and for discriminating against frequencies above a second rollover frequency so that the cutoff frequency responses of said filter means overlap at a crossover frequency, said

d. means for varying the magnitude of said crossover frequency by variance of elements in said filter means.

10. The system of claim **9** wherein said first modulation network comprises four of said tremulant circuits connected in series and said second modulation network comprises three of said tremulant circuits connected in series.

11. The method of modulating an electrical signal comprising:

a. filtering different frequency bands from a plurality of parallel phase-shifted signals each representative of said electrical signal,

b. varying the frequency bands filtered from said phase-shifted signals,

c. combining the filter signals, and

d. varying the rate of variance of the frequency bands filtered from said phase-shifted signals.

12. The method of claim 11 wherein said phase-shifted signals are 180° out of phase.

13. The method of claim 11 and further comprising:

a. filtering frequencies above a selected first frequency from one of said phase-shifted signals, and

b. filtering frequencies below a selected second frequency from another of said phase-shifted signals.

14. The method of imparting tremulant effects into an audiofrequency output from a musical instrument comprising:

a. generating a pair of parallel phase-shifted electrical signals each representative of said output,

b. filtering frequencies above a preselected reference frequency from one of said electrical signals,

c. filtering frequencies below said reference frequency from the other of said electrical signals,

d. combining the filtered electrical signals, and

e. varying said reference frequency.

15. The method of claim 14 wherein the phases of said electrical signals are 180° out of phase.

16. The method of claim 14 wherein the cutoff frequency responses of said filtered electrical signals overlap at a crossover frequency.

17. The method of claim 16 wherein said crossover frequency occurs at the 50-percent level of each of said cutoff frequency responses.

18. In a tremulant system for musical sound the combination of:

first means for producing a first electrical signal representative of sound produced by a musical instrument,

second means for cyclically shifting the phase of said first electrical signal to produce a second electrical signal in which the phase angle is cyclically varied relative to the first electrical signal by an angle greater than about 540°, and

third means for summing said first electrical signal and said second electrical signal to produce a third electrical signal that is both frequency and amplitude modulated.

19. The system of claim 18 wherein the first and second signals are summed in a ratio ranging from about 1:2 to about 2:1.

20. The system of claim 18 wherein the phase of the first electrical signal is shifted through an angle approximately equal to $2\pi n$, where n is an integer.

21. The combination defined in claim 18 further characterized by:

fourth means for producing audible sounds in response to the third electrical signal.

22. The combination defined in claim 21 wherein the first means includes a musical instrument.

23. The combination of claim 18 wherein the second means includes means for selectively shifting the phase of the first electrical signal at a first cyclical rate of from about 3 to about 10 cycles per second, and at a second cyclical rate of from 0 to about 3 cycles per second.

24. The combination defined in claim 23 wherein the second means further includes means for changing from one cyclic rate to the other cyclic rate in a predetermined manner to stimulate the inertial characteristics of a rotating speaker.

25. The combination defined in claim 18 wherein the second means includes:

means for cyclically shifting the phase of said first electrical signal at a vibrato rate, and

means for iniating the cyclic phase shift by progressively increasing the cyclical rate to stimulate the inertial characteristics of a rotating speaker.

26. The combination defined in claim 18 wherein the second means includes:

means for cyclically shifting the phase of said first electrical signal at a vibrato rate, and

means for terminating the cyclic phase shift by progressively decreasing the cycle rate to stimulate the inertial characteristics of a rotating speaker.

27. The tremulant system comprising means for producing a sound from a stationary speaker that is tremulated at a rate such as to simulate the sound produced by a speaker rotating at said rate, said means including means for progressively initiating and progressively terminating the tremulant rate to simulate the inertial characteristics of the rotating speaker.

28. The method for producing a musical sound from a fixed speaker approximating that produced by a rotating speaker which comprises cyclically shifting the phase of a first signal representative of the musical sound at a rate corresponding to the rate of rotation of the speaker, said phase being shifted through a phase angle in excess of about 540° to produce a second signal, and summing the first signal and the second signal to produce a third signal representative of musical sound produced by a rotating speaker.

29. The method of claim 28 wherein the first and second signals are summed in a ratio between about 2:1 and about 1:2.

30. The method of claim 29 wherein the phase of the first signal is shifted through a phase angle of about $\phi=2\pi n$ where n is an integer.

31. The tremulant system for producing musical sound comprising:

variable phase shift means for shifting the relative phase of first and second signals each representative of the same musical sound, the variable phase shift means comprising a plurality of variable phase shift stages, each stage comprising a transistor, a biasing network for the transistor, a capacitor connecting the collector of the transistors to the output of the stage, and a variable resistance connecting the emitter of the transistor to the output, the variable resistance of each stage being varied by said means for cyclically varying the degree of phase shift of the phase shift means,

means for cyclically varying the phase shift means so as to vary the degree of relative phase shift from a minimum value to a maximum value at a selected vibrato rate, and

a summation network for summing the first and second signals to produce a tremulant signal.

32. The tremulant system of claim 31 wherein at least one of the stages includes means for selectively limiting the maximum and minimum values of the variable resistance to adjust the total cyclic phase shift produced by the phase shift means.

33. The tremulant system for producing musical sound comprising:

variable phase shift means for shifting the relative phases of first and second signals, each representative of the same musical sound,

means for cyclically varying the phase shift means so as to vary the degree of relative phase shift from a minimum value to a maximum value at a selected vibrato rate,

a summation network for summing the first and second signals to produce a tremulant signal, and

phase shift means for selectively varying the relative phase of the first and second signals at the extremes of phase shift produced by the phase shift means.

34. The tremulant system for producing musical sound comprising:

variable phase shift means for shifting the relative phase of first and second signals each representative of the same musical sound,

means for cyclically varying the phase shift means so as to vary the degree of relative phase shift from a minimum value to a maximum value at a selected vibrato rate, and

a summation network for summing the first and second signals in an amplitude ratio from about 2:1 to about 1:2 to produce a tremulant signal.

35. The tremulant system for producing musical sound comprising:

variable phase shift means for shifting the relative phase of first and second signals each representative of the same musical sound,

means for cyclically varying the phase shift means so as to vary the degree of relative phase shift from a minimum value to a maximum value greater than the minimum value by about 540° at a selected vibrato rate, and

a summation network for summing the first and second signals to produce a tremulant signal.

36. The tremulant system for producing musical sound comprising:

first and second circuits each comprising variable phase shift means for shifting the relative phase of first and second signals each representative of the same musical sound, means for cyclically varying the phase shift means

so as to vary the degree of relative phase shift from a minimum value to a maximum value at a selected vibrato rate, a summation network for summing the first and second signals to produce a tremulant signal,

high pass filter means in the first circuit for excluding a low frequency range,

low pass filter means in the second circuit for excluding a high frequency range, and wherein

the phase shift means in the first and second circuits are cyclically varied at different vibrato rates.

37. The tremulant system of claim 36 wherein

the phase shift means in the first circuit produces a relative phase shift of about 720°, and

the phase shift means in the second circuit produces a relative phase shift of about 540°.

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