

[54] **MULTIDIRECTIONAL SOUND SYSTEM**

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[22] Filed: **June 15, 1970**

[21] Appl. No.: **46,345**

Related U.S. Application Data

[63] Continuation-in-part of Ser. Nos. 697,103, Jan. 11, 1968, and Ser. No. 853,822, Aug. 28, 1969, and Ser. No. 888,440, Dec. 29, 1969, Pat. No. 3,632,886.

[52] U.S. Cl. **179/1 GQ, 179/100.4 ST**

[51] Int. Cl. **H04h 5/00**

[58] Field of Search. **179/1 G, 1 GP, 15 ST, 179/100.4 ST, 100.1 TD**

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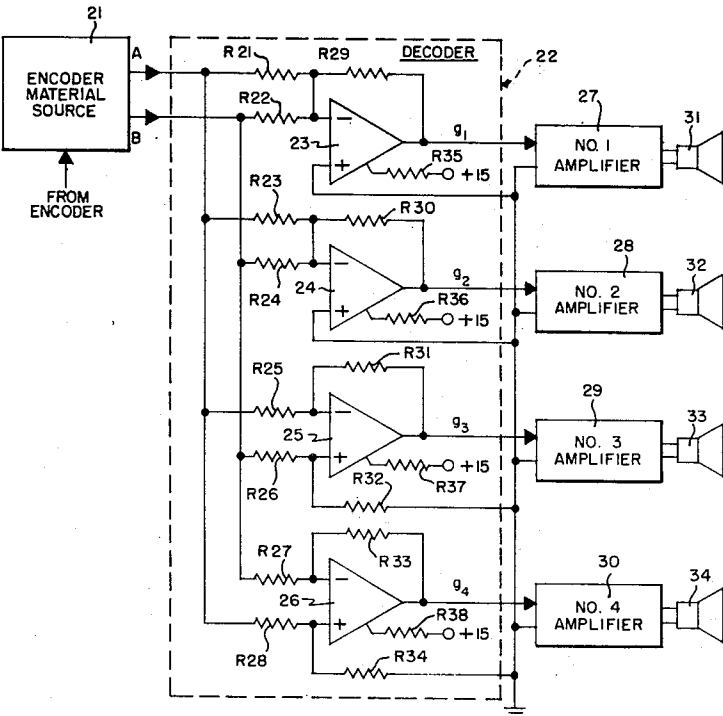
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[57] **ABSTRACT**

There is disclosed a sound system for producing at least three and typically four sound outputs from respectively different directions from the listener wherein the sound content per se and the directional information

are encoded on a conventional standardized two-channel record or on a transmission by a conventional two-channel broadcasting medium such as stereo FM. The system is maximally compatible with existing systems in the sense that reproduction on existing two-direction (stereo) or one-direction (mono) sound systems is completely satisfactory although, of course, the extent of directionality reproduction is limited by the inherent characteristics of such existing systems. In a typical example, the system provides for four directional sound inputs with equal, 90° separation around a circle. The four sound inputs are fed to two sound channels, for example stereo recording or transmission channels. Each of the four sound input channels is fed in part to each of the two stereo channels but the polarity and/or amplitude of each sound input channel is different in each of the stereo channels. Conventional analog computer electronic circuits may be utilized to transform the four sound input signals into two stereo channels according to prescribed formulae. The system provides for reproduction of sound from four loudspeakers located in the four corners of a room and having nominal positions with respect to the listener of left front, right front, left rear and right rear. The two stereo channels are combined according to different formulae setting forth different amplitudes and/or polarities to produce four output sound channels. Assuming these four directions correspond to directions of the four input sound channels, and sound originating from a particular sound input channel is reproduced predominantly in the corresponding loudspeaker. Refinements for the system control the gain for the respective loudspeakers to permit sound from a particular input sound channel to be localized to a particular corresponding output loudspeaker. In generalizations of the system, the number of inputs and the number of loudspeakers may be greater or less than four (but always more than two) and the numbers and/or directions of the input sound channels may not correspond to the numbers and directions of the outputs feeding the loudspeakers.

14 Claims, 12 Drawing Figures



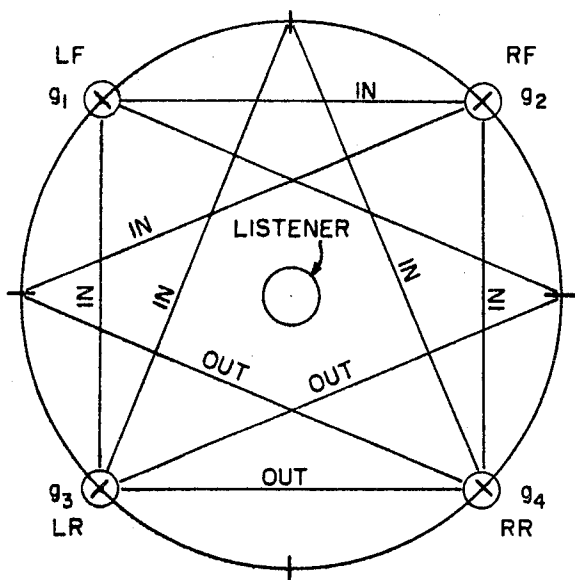
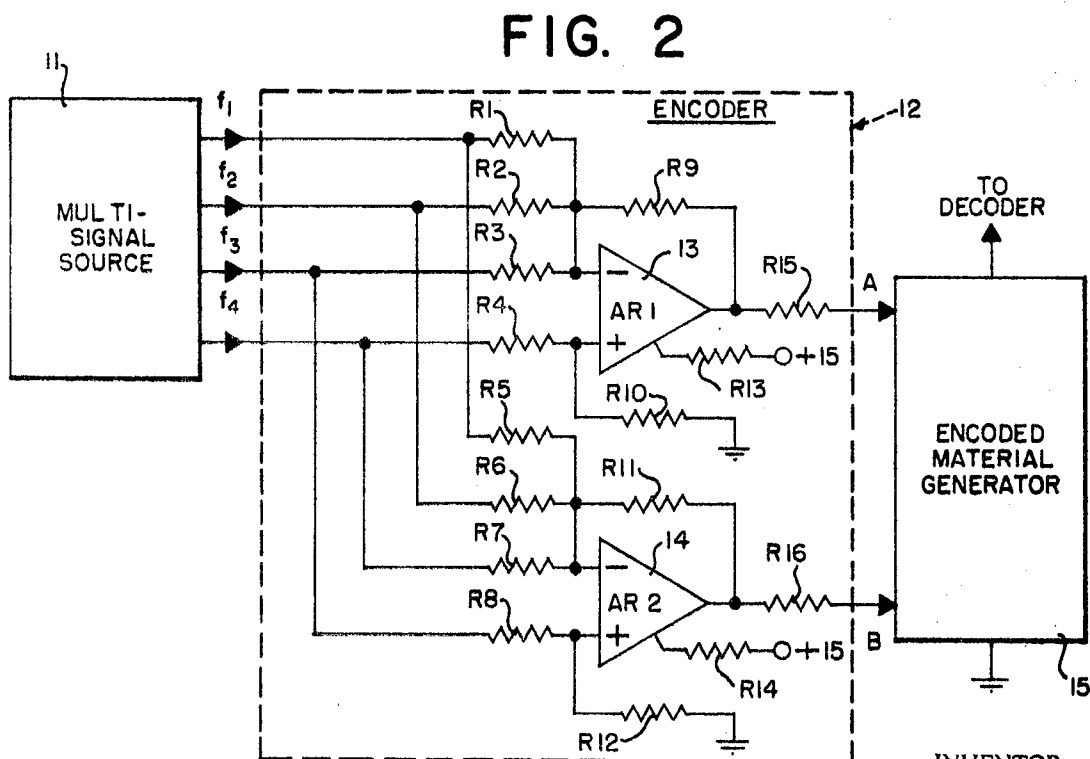


FIG. 1



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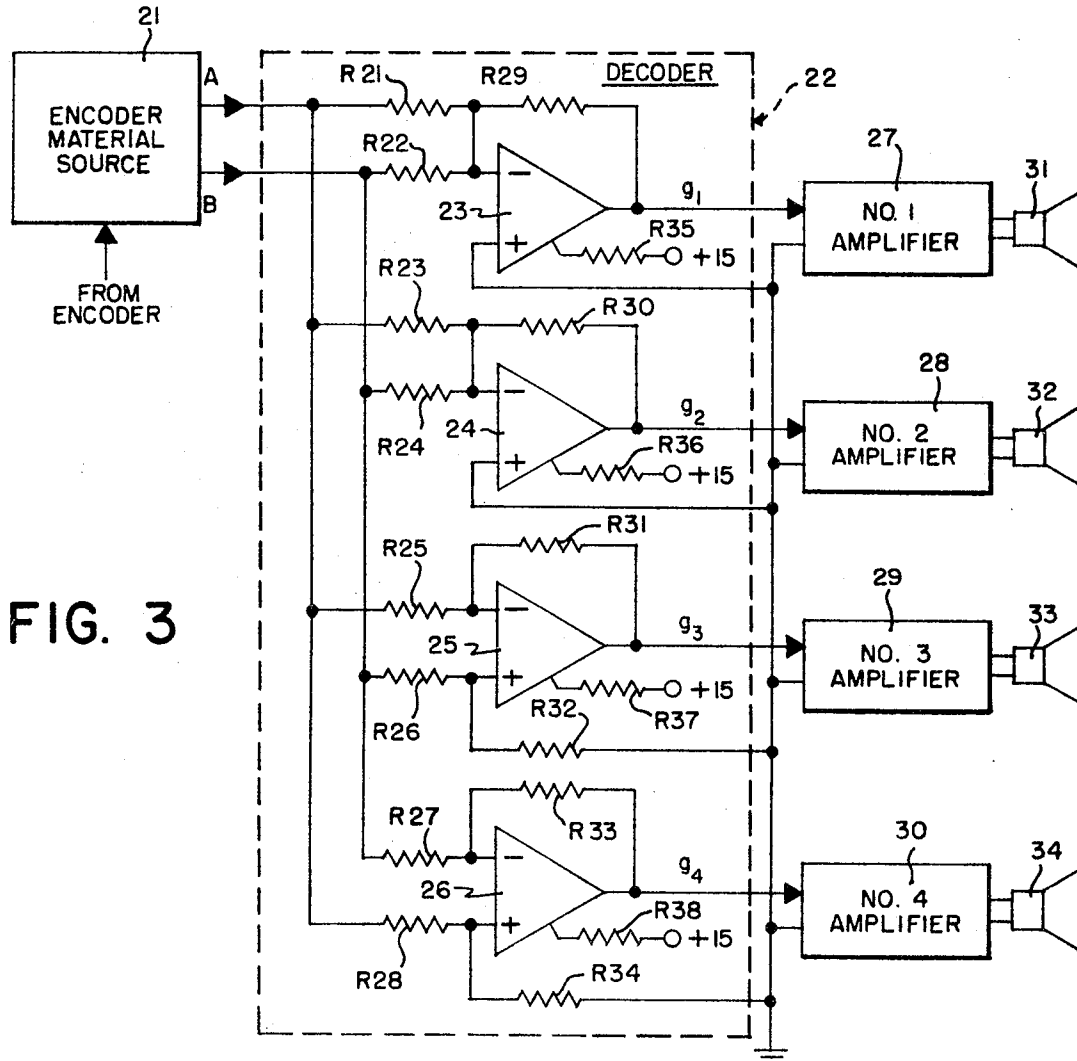


FIG. 3

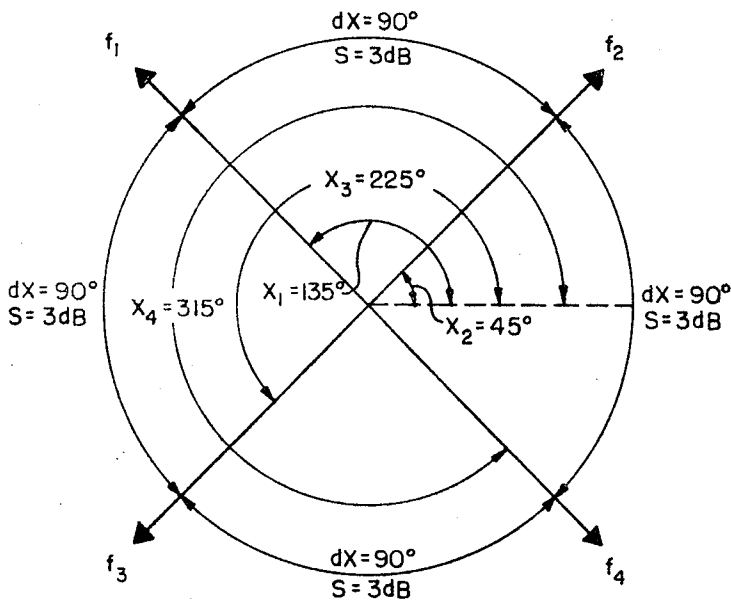


FIG. 4

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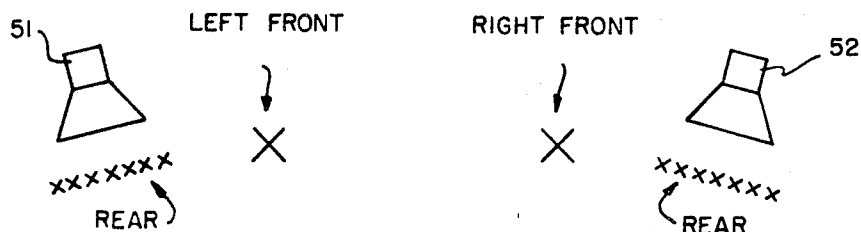


FIG. 5

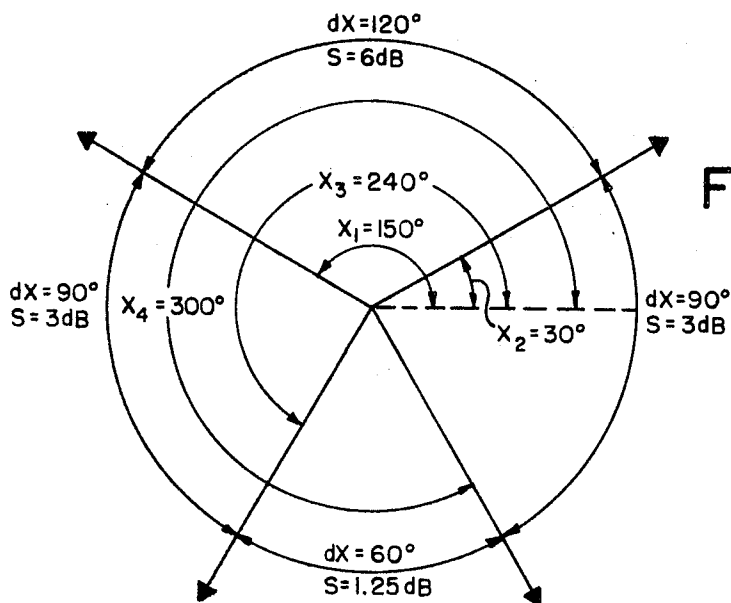


FIG. 7

FIG. 6

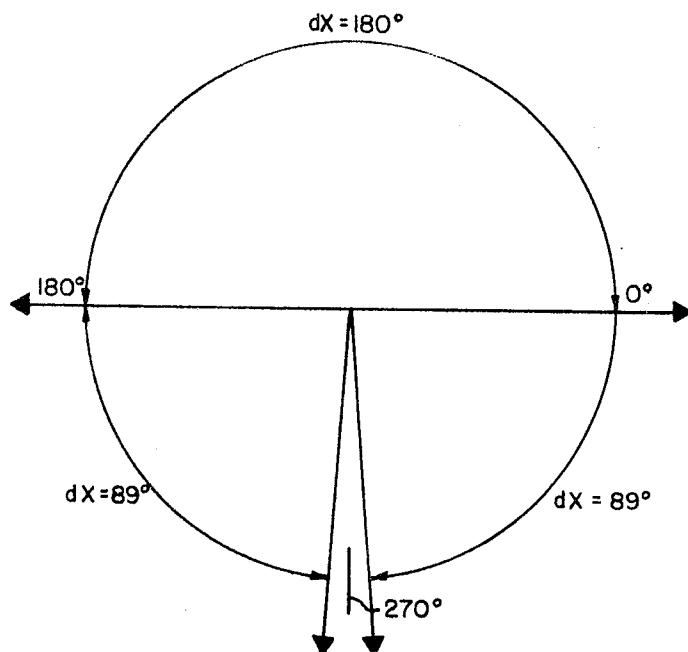
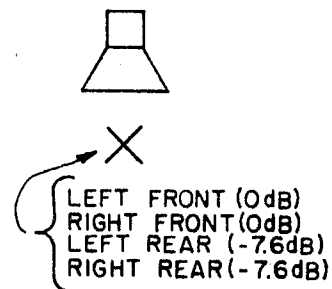


FIG. 8

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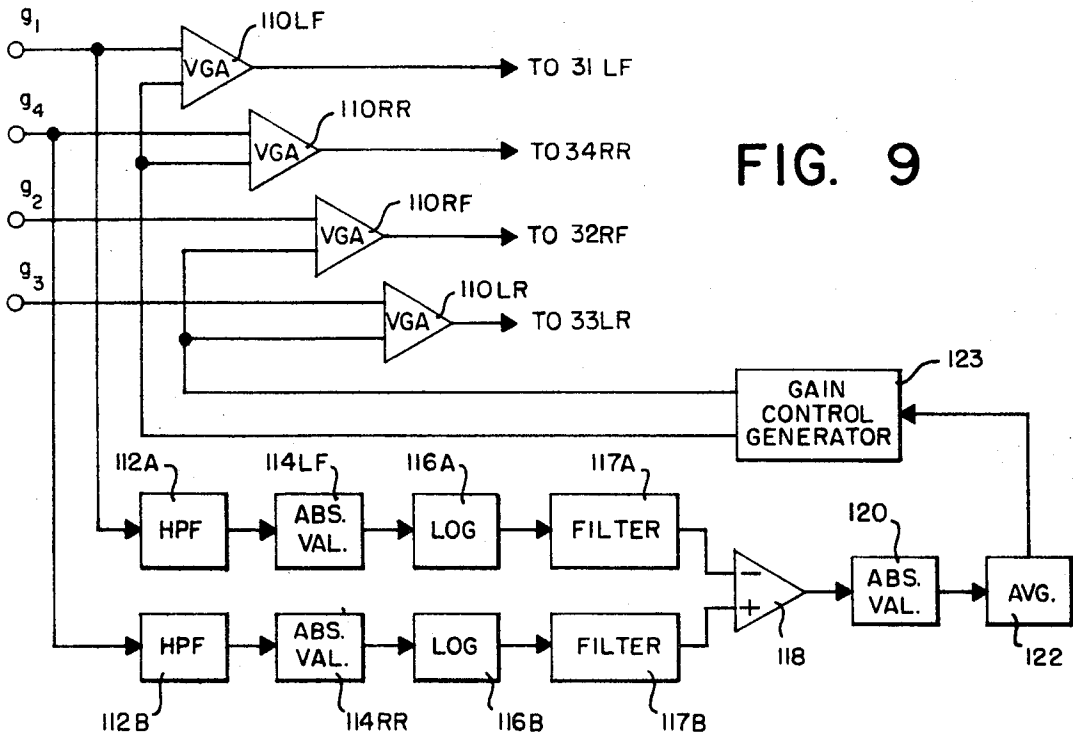
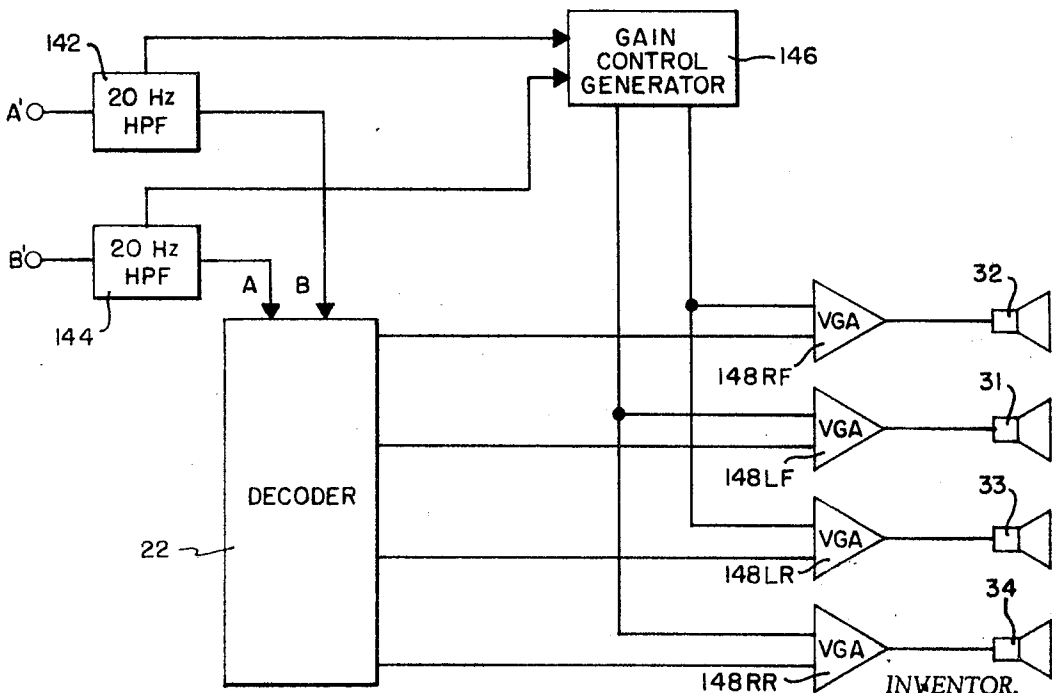


FIG. 9

FIG. 12



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MULTIDIRECTIONAL SOUND SYSTEM

This application is a continuation-in-part of prior copending application Ser. No. 697,103 filed Jan. 11, 1968 entitled STEREOPHONIC SOUND SYSTEM; 5 Ser. No. 853,822 filed Aug. 28, 1969 entitled STEREOPHONIC RECORDING AND TRANSMISSION SYSTEM (now abandoned); and application Ser. No. 888,440 filed Dec. 29, 1969 entitled QUADRASONIC SOUND SYSTEM now U.S. Pat. No. 3,632,886, all in the name of Peter Scheiber.

A complete system in accordance with the invention would include multidirectional sound pickup apparatus, encoding apparatus for converting the multiple channels from the pickup apparatus into only two separate electronic channels, recording apparatus and playback apparatus (or transmitting apparatus and receiving apparatus), decoding apparatus for producing multidirectional sound electrical signals correlating respectively with the multidirectional sound input signals, and 10 audio amplifiers and loudspeakers or equivalent apparatus for producing a multidirectional sound effect for one or more listeners. Multidirectional shall herein be interpreted to mean representative of at least three directions of sound, and in a typical case four directions of sound. It is permissible and in fact highly desirable for certain portions of the system described above to be strictly conventional. For example, transmitting and receiving portions of a system would typically consist of a conventional stereo FM broadcast transmitter and an FM broadcast receiver.

For many years the enjoyment of stereo or bidirectional sound reproduction has been a common reality, at least in this country. However, such bidirectional sound reproduction apparatus has serious inadequacies in reproducing music or other audio entertainment with an effect approaching that obtainable with live performances.

The desirability of expanding the bidirectional sound techniques to multidirectional sound techniques has been expounded in prior copending Scheiber patent applications and elsewhere. The desirability of multidirectional sound systems over bidirectional sound systems is intuitively apparent when one appreciates that the bidirectional sound system can only simulate sound sources existing within a limited angle of substantially less than 180°, whereas a multidirectional sound system can simulate sounds originating from any direction, thus encompassing 360°. The augmented realism and impact of multidirectional sound over bidirectional sound is fully borne out by actual experience.

In theory, there is no obstacle to creating multidirectional sound systems. Thus, a four-direction sound system for magnetic tape can be extrapolated in an obvious way from stereo tape systems. Instead of using two magnetic tracks on the magnetic tape, one uses four tracks. In effect, the stereo system which resulted by effectively doubling the monaural system is again doubled to produce a four-direction system. Such a four-track sound system, while feasible in theory, fails to solve numerous practical difficulties. The essential difficulty is that one has effectively doubled the entire system for reproduction of sound. Thus, if one wishes to transmit by radio, it would require two stereo FM radio stations rather than the one stereo FM station required to broadcast bidirectional sound. For magnetic recording, twice as many record or playback heads are re-

quired, twice as many tape tracks, and twice as much tape. The difficulty in the case of disc recordings is even greater since it appears that two grooves or tracks on the disc would be required, or else some complex subterfuge to obtain an equivalent recording capacity, neither of which has been found to be practical.

In accordance with the present invention, it has been found that substantially all the directionality information which can be reproduced by four loudspeakers and appreciated by a listener can be recorded and transmitted without doubling and in fact without substantially increasing the basic information-carrying capacity of two conventional audio channels (for example those of a stereo record or stereo FM radio broadcast).

In the system according to the invention, the directionality information is encoded in the amplitude and phase (or polarity) relationships of each multidirectional input signal in one of the stereo channels as compared to the other channel. While the directionality information is not recorded with a precision equal to that achieved for the frequency components making up the audio information per se, this is quite unimportant in view of the inadequacies of reproduction and evaluation of directional information in the system overall (including the listener). By way of example, note that in any directional sound system there are a finite number of loudspeakers, and sounds emanating other than from those precise positions must be approximated by activating loudspeakers in different positions with appropriate amplitudes. Thus a sound which should emanate from directly in front of the listener must be approximated by sound from both a left front and a right front speaker.

In the present invention, the basic directional encoding and decoding arrangement utilizing amplitude and phase relation between the two stereo channels may be augmented by a gain control arrangement for the output signals. Such a gain control system permits the sound to be localized in one loudspeaker to an extent greater than would be achieved with the basic encoding and decoding system.

In a preferred embodiment, the invention also provides a system which is maximally compatible with existing stereo FM broadcasting and with stereo disc recording. For example, if a disc record in accordance with the present invention is played and the sound is reproduced from a monaural amplifier or monaural FM radio receiver, or from a stereo amplifier or from a stereo FM radio receiver, the result is highly acceptable monaural or stereo sound reproduction as the case may be. The reproduction in either case includes all four sound inputs of the recording but with the rear sound input diminished in amplitude from the amplitude they would have if reproduced with a four-loudspeaker system in accordance with the invention. No directionality distortion is introduced in mono or stereo reproduction in the sense that the right channels and the left channels are produced equally in the monaural playback and in the stereo playback are produced correctly in the best possible approximation to the four-speaker reproduction.

For simplicity of explanation, it is convenient to think in terms of a multidirectional sound system with four loudspeakers situated in the corner of a substantially square room reproducing material having four input signals corresponding in direction to the four loudspeakers utilized in reproduction. Such an arrangement

is encompassed in the preferred embodiment of the system. However, a generalization of the system is presented such that the number of inputs to the encoder are not limited to four, nor are they limited as to the direction which is to be represented by an output. In fact, the direction represented by an input signal is determined by the values of certain resistors, and it is readily possible to provide variable resistor networks such that the direction represented by an input can be varied at will or can be set for any desired direction. In a similar manner, the direction represented by the output loudspeakers can be changed from the previously described 90° separation to some other values. The direction associated with a loudspeaker output may thus be changed to accommodate the necessity of placing a speaker in an abnormal position. However, the position represented by the loudspeaker output does not necessarily have to conform to its physical position. Interesting effects can thereby be obtained. It will be seen that one can increase or decrease the angle which a distributed sound source such as an orchestra appears to subtend. One can thus control the signal to the loudspeakers to create the effect of moving from the rear of a hall where the orchestra subtends a relatively small angle to the front of the hall (or in fact the podium) where the orchestra subtends a much larger angle.

The assignment of any desired direction to a loudspeaker output may also prove desirable for special situations such as automobile-installed systems wherein the loudspeaker placement may best be other than the left front, right front, left rear, right rear placement usual in a living room or studio.

In addition to providing the advantages described above, it is an object of the present invention to provide a multidirectional sound system such that records or transmissions in accordance with the system may be played on existing standard bidirectional or monodirectional equipment with completely satisfactory results comparable to recordings or transmissions produced with only stereo or mono information content.

It is another object of the present invention to provide a multidirectional sound system wherein three or more sound input signals are processed and transmitted over two channels, which two channel signals are inversely processed to provide three or more multidirectional output signals correlating to the input signals.

It is another object of the present invention to provide a multidirection sound system in which the assigned direction for sound inputs or outputs may be determined by the assignment of amplitude values as determined by resistor values or the like with the result that the effective direction assigned to an input sound signal or that assigned to an output sound signal can be adjustably determined within a wide angle.

Other objects and advantages will be apparent upon consideration of the following description in conjunction with the appended drawings in which:

FIG. 1 is a diagram showing a typical speaker placement in relationship to a listener and certain desirable phase or polarity relationships for apparatus according to the invention;

FIG. 2 is a schematic diagram of an encoder section of apparatus according to the present invention;

FIG. 3 is a schematic diagram of a decoder and reproduction section of apparatus according to the present invention;

FIG. 4 is a diagram useful in explaining directionality effects obtained by a typical system in accordance with the invention;

FIG. 5 is a diagram useful in explaining the subjective effect of reproduction on conventional stereo reproduction equipment of four direction sound signals produced in accordance with the invention;

FIG. 6 illustrates the effect of reproduction on monaural reproduction equipment of four direction sound signals produced in accordance with the invention;

FIG. 7 is a diagram illustrating the directional effect obtainable with an alternative form of system in accordance with the present invention;

FIG. 8 is a diagram illustrating the directional effect of a further alternative system in accordance with the present invention;

FIG. 9 is a schematic diagram of a gain control arrangement for a four-directional system which may be adapted to decoding systems in accordance with the invention to produce greater localization of sound from individual ones of the four output loudspeakers;

FIG. 10 is a schematic diagram of an alternative form of gain control for a four-directional sound system in accordance with the invention;

FIG. 11 is a schematic diagram of a gain control signal generator for providing a low frequency gain control signal in recorded or transmitted material to properly control the gain in apparatus as illustrated in FIG. 12; and

FIG. 12 is a schematic diagram of a gain control system adaptable for use in conjunction with the described four-direction sound system wherein the localization of sound output to various loudspeakers is controlled by a low frequency signal.

AMPLITUDES AND POLARITIES FOR ENCODING AND DECODING

As previously stated, the present system takes three or more directional sound input signals and combines them into two conventional audio information channels (such as utilized in stereo recording or broadcasting) in a manner to impart multidirectional sound direction information.

According to the invention, there are essentially two parameters to be considered in processing the multidirectional sound signals. These two parameters are phase and amplitude. It is convenient to limit consideration of phase relationships to only two different discrete phase relationships, namely zero degrees (in phase) and 180° (out of phase). These phase relations may also be treated as a simple reversal in polarity or sign.

Considering first the amplitude relationships, it will be noted that one wishes to have a formula for determining the amplitude with which a particular input sound signal is to be supplied to the A channel (left channel) of a conventional stereo recording or transmission system and the amplitude with which such signal is to be supplied to the B channel (right channel) of the system.

It will be seen that the appropriate amplitude relation for the A and B channels can be determined as a function of the direction assigned to the particular input signal. In this discussion, the direction assigned to the input signal will be identified by an angle x_1 for signal No. 1, x_2 for signal No. 2, and so on.

The angle of the position directly to the right of the listener is arbitrarily assigned the value of zero degrees and the angular progression is counterclockwise. Hence the positions, illustrated in FIG. 1 for example, of right front, left front, left rear and right rear would have angular position designations of 45°, 135°, 225° and 315° respectively. See also FIG. 4.

Using this convention, the amplitude of an input signal supplied to the A channel is equal to the amplitude of the input signal multiplied by the sine of one half the position angle. The equation for A signal amplitudes is given in Equation 1 of the Appendix hereinafter.

The amplitude of the signal supplied to the B channel is equal to the amplitude of the input signal multiplied by the cosine of one half the position angle. The equation for the B channel signal amplitudes is given in Equation 2 in the Appendix.

It should be noted that the terms in Equations 1 and 2 all have a positive sign, but that this is not intended to indicate the polarity or phase of the signals. The polarity is determined in accordance with the quadrant in which the direction angle lies as explained hereinafter.

It is also necessary, of course, to define the appropriate decoding process to produce output signals correlating with the three or more input signals and having a desired directional characteristic. The angular position convention for decoding is the same as for encoding. Each output signal g_1 , g_2 etc. has an amplitude equal to the A channel amplitude times the sine of one half the position angle for the output signal plus the amplitude of the B channel times the cosine of one half the position angle for the output signal. The decoding equation is given as Equation 3 in the Appendix. As before, the polarity or sign for the signals is determined by the quadrant in which the position angle lies rather than by Equation 3.

An important aspect of the system is the manner in which the phase or polarity relations for different angular position designations of output and input are related to the A and B channel signal polarities. In order to gain some intuitive understanding of the encoding and decoding criteria described above, it is useful to note the operation of the system for a particular input signal.

Consider an input signal which is assigned the angular position of left front or 135°. It can be shown that in accordance with the above encoding and decoding criteria, and assuming that the output loudspeakers have angular positions of 45°, 135°, 225° and 315°, the output correlating to the hypothetical input signal will be predominantly from the left front or 135° loudspeaker.

There will be no output from the right rear speaker and there will be some output from the right front speaker and the left rear speaker. In each of the latter two speakers, the power output will be one half the power (0.7 times amplitude) of the left front speaker level. The phase or polarity of the signal from the right front speaker and from the left front speaker are desired to be the same as are the polarities of the left front and left rear speakers. This is indicated in FIG. 1 by the notation "in" on the lines joining the left rear and left front and the right front and left front speakers.

The use of positive and negative polarities in the system requires that two adjacent speakers, at least, must be of opposite polarity or out of phase. According to the preferred embodiment of the invention, only the two rear speakers have this out-of-phase condition, this

being most compatible with the prevalent situation in which the principal subject material rarely originates predominantly from the rear speakers.

Another important consideration is that in standardized FM stereo-radio broadcasting, a monaural receiver reproduces a signal for the listener corresponding to the sum of the A channel and the B channel in equal amplitude. Referring to the decoding relationship, it will be seen that the position angles which yield equal A and B amplitudes are 90° and 270°. One desires that the monaural radio receiver have a position angle corresponding to front center or 90°. Hence, the A channel and B channel must be combined with the same polarity or in phase for the front center or 90° position. This also means that a four-direction broadcast received on a stereo FM receiver would produce left front sounds and right front sounds from the left and right speakers respectively which are in phase (of the same polarity). This is obviously the desired situation. In other words, for one-direction and two-direction playback compatibility, the present invention provides that the front center direction be represented by A equal to B and of the same polarity, that is, the position angle x equals 90° and A is at the left and B is at the right.

In reproduction of four-directional sound, the most important direction is obviously front center. Due to the predetermined arrangement of speakers in the four corners, the sound image for a front center directional sound input is necessarily a ghost image between the front pair of speakers. It is important that in addition to the front speakers having equal amplitude for this situation, that they be in phase. Such a situation prevails in FIG. 1. It is also desirable that this front center sound input, to the extent that it is reproduced in the rear speakers, be reproduced in the same polarity or in phase. It will be seen in FIG. 1 that this situation also prevails.

The situation with respect to those images existing between a front speaker and a corresponding rear speaker is not so critical but it is desirable that any out-of-phase or opposite polarity reproduction of such signal be in an opposite rear speaker and that is also shown in FIG. 1.

As previously mentioned, one wishes to have any ghost image existing between two speakers produced in phase in each of the flanking speakers and this situation is maintained to the maximum extent possible as shown in FIG. 1 (excepting only the ghost images in the rear quadrant).

It will be seen that a particular assignment of polarities or phase relationships for the encoding and decoding formulas must be observed to achieve the desirable reproduction relationships depicted in FIG. 1. Referring to Equations 1, 2 and 3, the proper polarities can be summarized as follows. All sine terms should be assigned a positive value for left front, right front and left rear quadrants, and a negative value for the right rear quadrant. All cosine terms should be assigned a positive value for the left front, right front and right rear quadrants and a negative value for the left rear quadrant. The foregoing polarities or signs are in lieu of the sign for the trigonometric function for the particular quadrant. It is of interest that the difference between the assigned value and the trigonometric values from zero through 360° is only different in the fourth quadrant, i.e. the right rear. If one assigns the right rear

quadrant angle values of from minus 90° to zero rather than 270° to 360°, then the algebraic sign of the trigonometric functions would correspond to the desired values as derived from the analysis illustrated in FIG. 1.

ENCODER APPARATUS

Suitable apparatus for encoding in accordance with the system herein described is shown in FIG. 2. It must be noted that the particular form the apparatus takes is subject to great variation. As will be seen from Equations 1 through 3, the operation to be performed is quite simple in that it involves multiplying respective audio frequency inputs by predetermined constants and adding or subtracting the products so obtained to derive an encoded A channel or a B channel signal. Numerous forms of conventional and readily available electronic analog computer circuits or components may be utilized to perform this operation.

Referring to FIG. 2, multidirectional signals f_1 , f_2 , f_3 and f_4 are obtained from a multisignal source 11. The multisignal source would typically consist of a multiple track tape recording produced at a recording session with various microphones or other audio input devices representing sound input signals to be assigned angular position values for multidirectional sound reproduction. The angular position value assigned to a particular recorded sound signal may correspond to an actual direction from a listener position in an actual recording session. The assigned angular position value for a particular sound signal can, however, just as well be purely arbitrarily assigned to produce a desired directional sound effect.

A schematic circuit diagram for the encoder is shown within the dashed outline box 12.

The encoder circuit is shown with four inputs for separate and distinct sound input signals but it should be noted that more inputs may be provided, and the number of inputs is not determined by the number of output loudspeakers (which would normally be four in number). It will be noted that with more than four inputs, two or more inputs may be assigned to the same quadrant or to the same position angle resulting in the encoder serving the function of a mixing and sound effect control apparatus as well as an encoder. One sound signal may also be supplied to two encoder inputs for specific effects.

The function of the encoder of FIG. 2 is to process the signals f_1 , f_2 , f_3 and f_4 in accordance with Equations 1 and 2 to arrive at output signals A and B.

A pair of operational amplifiers 13 and 14 together with appropriate input resistors, feedback resistors and other resistors utilized in a well-known manner are employed to derive the output signals A and B. The amplifiers 13 and 14 may, for example, be Philbrick-Nexus 1011 amplifiers which have the advantage of being capable of driving 600 ohm characteristic impedance output lines directly. Numerous other amplifiers may also be used, noting of course that they must have suitably high gain over the full audio frequency band for which the encoder is intended. Fifteen cycles to fifteen thousand cycles would normally be ample frequency coverage.

Resistors R1 through R8 in FIG. 2 are input resistors, the resistance values of which may conveniently be utilized to determine the position angle which is to be assigned to each of the four multidirectional input sig-

nals. The circuit illustrated in FIG. 2 is intentionally selected so that it is not limited to a prescribed set of position angles for the respective input signals. Rather, a formula has been derived which permits the position angles to be set at different values over a wide range. Since certain position angles are associated with negative polarity and other position angles are associated with positive polarity for the sine and cosine terms of Equations 1 and 2, a limit is imposed to some extent on the assignment of position angles to the respective inputs. Accordingly, signal f_1 and signal f_2 may be located anywhere in the first or second quadrants. Signal f_3 may be located anywhere in the third quadrant, and signal f_4 may be located anywhere in the fourth quadrant.

It may also be noted that for circuit economy, the amplifiers 13 and 14 are provided with three inputs to their negative input terminal (not counting the feedback) and only a single input to the positive input terminal. One could also simply provide all inputs to the one negative input terminal and utilize an inverter amplifier in series in any of the inputs which one desired to provide with an opposite polarity.

In the circuit of FIG. 2, resistors R9 and R11 are feedback resistors, resistors R10 and R12 are ground resistors, and resistors R13 and R14 are trimming resistors. Resistors R15 and R16 are output resistors.

In accordance with well-known analog computer techniques, the values of resistors R9 through R12 are selected to make circuit values fall within a convenient range and to make input impedances sufficiently high to avoid loading associated circuits. These values would usually be in the range between ten thousand and several hundred thousand ohms.

The values of resistors R13 and R14 are selected in accordance with operational amplifier manufacturer instructions to null DC offset. Resistors R15 and R16 are small isolating resistors to prevent loading from affecting operational amplifier stability and may be of the order of thirty ohms. The values of resistors R1 through R8 depend upon the angular position assigned to corresponding inputs as set forth in Equations 4 through 11 in the Appendix.

As a specific example of an encoder circuit, one may utilize a basic configuration of input position angles as illustrated in FIG. 4. As seen from FIG. 4, input f_1 is at 135°, input f_2 is at 45°, input f_3 is at 225°, and input f_4 is at 315°. The equations for the amplitudes of the A channel and B channel signals are given in Equations 12 and 13, and the values for resistors R1 through R16 are as follows:

R1 = 108.2k

R2 = 261.3k

R3 = 108.2k

R4 = 422.1k

R5 = 261.3k

R6 = 108.2k

R7 = 108.2k

R8 = 422.1k

R9 = 100.0k

R10 = 50.0k

R11 = 100.0k

R12 = 50.0k

R13, R14 are selected to cancel amplifier DC offset
R15, R16 = 30 ohms

It may be noted that if all (four or more) inputs to each operational amplifier are to the negative terminal and inverters are provided for inputs desired to be of

different sign, then simple relations (such as for R1 and R5) prevail for all input resistors and the two resistors associated with each input have values solely determined by that input's position angle. Variable resistors can thus be employed which are calibrated to provide any desired position angle (at least over one quadrant, 90°) for respective inputs.

DECODER APPARATUS

FIG. 3 illustrates an exemplary decoder schematic circuit diagram as part of the playback portion of the overall system. Similarly to the decoder schematic circuit diagram, the circuit illustrated in FIG. 3 is one way to implement Equation 3. Other known electronic analog computer circuits could also be used within the scope of the invention.

In FIG. 3, an encoder material source produces two electrical signal outputs representing an A channel and a B channel. The encoder material source could, for example, be a conventional stereo record player playing a record of material encoded by the apparatus of FIG. 2. Alternatively, the encoder material source could be in stereo FM radio receiver receiving encoded material from a transmitter that had been either encoded from a live broadcast or had been encoded on a two-channel tape or disc record for playback over the FM stereo transmitter. In any event, the audio signal channels A and B will typically be standard stereo transmission channels.

The A and B outputs of the encoder material source are the sole inputs to the decoder circuit contained within the dashed box 22 in FIG. 3.

A plurality of operational amplifiers 23, 24, 25 and 26 are provided which respectively generate four directional outputs for four directional loudspeakers.

The A channel and B channel inputs are supplied to the operational amplifiers with a particular amplitude ratio and polarity relationship determined by the position angle assigned to the particular operational amplifier and its associated loudspeaker.

Input resistors R21 and R22 determine the amplitude ratios of the channel A signal and channel B signal supplied to amplifier 23, resistors R23 and R24 serve this function with respect to amplifier 24, resistors R25 and R26 serve this function with respect to amplifier 25, and resistors R28 and R27 serve this function with respect to amplifier 26.

R29, R30, R31 and R33 are feedback resistors. R32 and R34 are ground resistors and R35, R36, R37 and R38 are trim resistors, all selected and used in accordance with known electronic analog computer techniques.

Outputs g_1 , g_2 , g_3 and g_4 from amplifiers 23, 24, 25 and 26, respectively, are each supplied to the corresponding one of four power amplifiers 27, 28, 29 and 30.

Power amplifiers 27 through 30 feed respective loudspeakers 31 through 34. Loudspeakers 31 through 34 are, of course, arranged for directional sound effects, for example as illustrated in FIG. 1.

Amplifiers 27 through 30 and loudspeakers 31 through 34 may be of conventional form. While illustrated as a single loudspeaker, each of the loudspeakers 31 through 34 may comprise a loudspeaker system and enclosure for improved audio reproduction. Similarly, amplifiers 27 through 30 may have controls, indicators

and other features normally associated with audio power amplifiers.

It will be noted that the inputs to amplifier 23 from channel A and channel B are of the same polarity as is also the case with amplifier 24. On the other hand, the B input to amplifier 25 and the A input to amplifier 26 are of the opposite polarity.

With the specific polarity arrangement illustrated, amplifier 23 has an output which may be assigned a position angle anywhere in the left front or right front quadrant, and the same is true of amplifier 24. The output of amplifier 25 may be assigned a position angle anywhere in the left rear quadrant, and the output of amplifier 26 may be assigned a position angle anywhere in the right rear quadrant. As previously explained, the position angle assigned for the operational amplifier output feeding a particular loudspeaker may or may not correspond to the actual physical position of the loudspeaker in the listening room.

If the position angles for the loudspeakers 31, 32, 33 and 34 are desired to correspond to the position angles illustrated in FIG. 1 (and thus to the input position angles illustrated in FIG. 4), the relative amplitudes of stereo channels A and B in each of the operational amplifier output signals g_1 , g_2 , g_3 and g_4 are readily calculated from Equation 3 in the Appendix, the results being given in Equations 14 through 17 in the Appendix.

To instrument the Equation 14 through 17 for the FIG. 3 decoder circuit, the following resistor values (in ohms) are appropriate:

R21 = 108.2k
R22 = 261.3k
R23 = 261.3k
R24 = 108.2k
R25 = 108.2k
R26 = 201.4k
R27 = 108.2k
R28 = 201.4k
R29, R30, R31 and R33 = 100k
R32 and R34 = 50k

R35, R36, R37 and R38 are selected to cancel amplifier DC offset. Amplifiers 23, 24, 25 and 26 may be the same as those described with reference to FIG. 2. Resistors R30 through R34 are selected to make circuit values fall in a convenient range.

Referring now to the complete system shown and described in FIGS. 2 and 3 where the position angles are as illustrated in FIGS. 1 and 4, the operation can be described in fairly simple terms.

It can be shown that an input signal f_i appears with greatest amplitude in the output signal g_1 , feeding amplifier 27 and loudspeaker 31. It also appears at a reduced level in output signal g_2 and output signal g_3 feeding loudspeakers 32 and 33 respectively. The level of output in speakers 32 and 33 is reduced by one half in power (3dB) or in amplitude to a level of 0.707. There is no output in signal g_4 corresponding to an input signal f_i .

Generalizing from the full power, half power and zero power relationship described above for the apparatus of FIGS. 1 through 4, it can be stated that output for a given input signal will be a maximum when the position angle of the output signal is the same as the position angle of the input signal. When the position angle of the output signal is different (by an angle dx) from the position angle of the input signal, the output will be

reduced by multiplying its amplitude by a factor equal to the cosine of half the angle of difference. An expression for the attenuation in decibels S_{dB} to which an input signal of a prescribed position angle is subjected in a particular output signal is given in the Appendix as Equation 18. This is also the separation in signal level which is obtainable between two output signals having a difference in position angle (dx) as prescribed.

It should be noted that while the position angle arrangement for inputs illustrated in FIG. 4 with inputs at 45°, 135°, 225° and 315° is convenient to use as the basis for a simple explanation, one should consider other inputs at other position angles to better understand the operation of the system. An input at 90° or front center is of especial interest.

A front center input obviously will be fed to loudspeakers 31 and 32 (left front and right front) equally and with slight attenuation (about 0.7 dB).

A front center input will also appear to a minor extent in outputs g_3 and g_4 (and in speakers 33 and 34). The level of this output is quite low, however, being attenuated by approximately 8 dB.

It should be kept in mind that the particular input and output position angles, presented in FIGS. 1 and 4 as a specific example and basis for description and explanation, are not the only possible embodiments nor necessarily the best embodiment for all purposes. Of course, the four-corner arrangement of loudspeakers as illustrated in FIG. 1 is a particularly practical one.

MONO AND STEREO COMPATIBILITY

Just as it is useful to consider the possibility of different input position angles than those of FIG. 4, it is also useful to consider different output position angles than those illustrated in FIG. 1 and corresponding to FIG. 4.

This is especially useful in considering compatibility with existing stereophonic and monophonic audio equipment. This existing equipment will be seen to have a corresponding position angle or position angles by which one can evaluate the monophonic and stereophonic reproduction of audio material encoded in accordance with the invention and particularly in accordance with the apparatus illustrated in FIG. 2.

Considering first stereophonic reproduction, it is well known, of course, that in such reproduction the stereo channel A is applied to a left loudspeaker and the stereo channel B is applied to a right loudspeaker (in stereo FM broadcast and reception, this occurs after numerous intermediate steps).

Referring to Equation 3 for decoding in the Appendix, it may readily be seen that reproduction of the A channel signal alone without any contribution from the B channel corresponds to a position angle of 180° (the cosine of one half of 180° is zero). Similarly, the reproduction of the B channel alone without any contribution from the A channel corresponds to a position angle of zero degrees (the sine of one half of zero degrees is equal to zero). From previous descriptions of the operation of the system, it will then be clear that a conventional stereo reproduction system will operate to reproduce in its left loudspeaker the subject matter that would have been reproduced in a left front and left rear loudspeaker of a four-directional system in accordance with the invention. Similarly, the right loudspeaker of a conventional stereo system would reproduce the material which would have been reproduced in the right

front and right rear loudspeakers of a four-directional system.

Using the same approach to the reproduction of four-directional material on monaural equipment, for example a monaural FM receiver receiving a broadcast from a stereo FM broadcast station, it will be noted that the in-phase and equal combination of the stereo A channel and B channel reproduced in such a system corresponds to a 90° position angle or a front center position (the sine of one half of 90° is equal to the cosine of one half of 90°). The effect on the listener of reproduction of four-directional material on either conventional stereo or conventional monaural equipment is schematically illustrated in FIGS. 5 and 6.

Referring to FIG. 5, a pair of speakers 51 and 52 are shown together with indications of typical sound image locations for four-directional material received by stereo equipment. Note that the image for left front four-directional audio material is, in fact, at left front in the two-speaker reproduction and the right front image is at right front, and that the left and right materials are properly balanced. It will be noted that the image for left front material and for right front material is displaced inwardly somewhat from the speaker location. This produces no material adverse effect, however, and is necessary so that the extreme speaker position available in the two-speaker system be reserved for the maximum right and left position angles of zero degrees and 180°. The rear material image from the left speaker 51 is indicated by a series of small x's. This is a schematic indication of the fact that the rear or reverberant channel material will be affected by a slight subjective outward displacement and spreading effect due to the out-of-phase or opposite polarity relation of the rear position angle material. This effect is entirely in keeping with the desired use of these position angles to create "ambience." Accordingly, the two-direction reproduction (stereo reproduction) of the four-direction material produces some emphasis for the front direction yet does not lose the rear direction material entirely. Thus reproduction on stereo equipment is nearly exactly what one would choose to have and provides excellent compatibility.

Referring to FIG. 6, a single speaker 53 is shown representing a monaural system speaker such as a monaural FM receiver speaker which might be tuned to a stereo FM broadcast transmitter. In such circumstances, the sound image obviously can only be in direct line with the loudspeaker and the relative power levels for various material will be: left front and right front zero dB and balanced, left rear and right rear material substantially diminished (-7.6 dB) but still present. Only the material encoded at exactly center rear (270°) will be eliminated entirely in monaural pickup. For mono reproduction, very little rear material, if any, is desired. Mono listening is usually done in less than ideal or even rather noisy environments, and it is important that primary (front) direction information should be emphasized as in fact results from the four-direction material monaural reproduction.

In regard to both monaural and stereo reproduction of the four-direction material, it should be noted that considerable control is exercised over the way that the material will be reproduced in stereo or mono by selection of position angles for the inputs to the encoder. Being aware of exactly how the material would be affected in stereo or mono reproduction, one may ar-

range that the monaural and stereo reproduction is of excellent quality as well as the four-directional reproduction, which is of course the main objective.

ENCODING WITH ALTERNATIVE POSITION ANGLE DESIGNATIONS FOR INPUTS

FIG. 7 shows alternative direction angle inputs which are particularly suitable for certain musical material to be encoded in accordance with the multidirectional system of the present invention.

In situations such as the concert hall, where the front encoder inputs will be required to carry the most critical primary program information, while the rear encoder inputs supply "ambience," or reverberation, one may wish to enhance the separation between the front encoder inputs at the expense of reducing the separation for the rear encoder inputs. This may be accomplished, for example as shown in FIG. 7, by prescribing a greater difference in position angle (α) between the front pair of inputs and less between the rear pair of inputs.

As shown in FIG. 7, x_1 equal 150° , x_2 equal 30° , x_3 equal 240° and x_4 equal 300° . The resulting encoding equation for channel A and channel B is given in the Appendix as Equations 19 and 20. The encoder resistor values for FIG. 2 which would provide the input position angles shown in FIG. 7 are given below.

R1 = 103.5k
R2 = 386.4k
R3 = 115.5k
R4 = 259.1k
R5 = 386.4k
R6 = 103.5k
R7 = 115.5k
R8 = 259.1k
R9, R11 = 100.0k
R10, R12 = 50.0k
R13, R14 are selected to cancel amplifier DC offset
R15, R16 = 30 ohms

It should be noted that the use of position angles for inputs as illustrated in FIG. 7 may or may not involve the use of decoder output position angles with the same values. Obviously, the decoder output position angles can likewise be varied without varying the input position angles.

To obtain output position angles corresponding to FIG. 7, the following resistor values in ohms may be utilized in FIG. 3.

R31 = 103.5k
R32 = 386.4k
R33 = 386.4k
R34 = 103.5k
R35 = 115.5k
R36 = 136.6k
R37 = 115.5k
R38 = 136.6k
R39, R40, R41, R43 = 100.0k
R42, R44 = 50.0k
R15, R16, R17, R18 are selected to cancel amplifier DC offset

The concept of separating the position angles for either the input or the output in the system to an angle greater than 90° for the front input or output signals is, of course, not limited to the particular position angle designations illustrated in FIG. 7. A limiting case for such separation is illustrated in FIG. 8 in which the front position angles have been spread to 180° . The

rear position angles have been set with a negligible separation. The position angles of FIG. 8, therefore, are for signal 1, 180° ; for signal 2, 0° ; for signal 3, 269° ; for signal 4, 271° . It is to be noted that signal 3 is still in the third quadrant and has the polarity relationships designated for that quadrant, while signal 4 is in the fourth quadrant and has the polarity relationships designated for that quadrant. If the extreme case shown in FIG. 8 were used as position angle designations for a decoder output where the speakers were located in the four corners of a room, the left front speaker would have the A channel alone supplied to it, the right front speaker would have the B channel alone supplied to it, the left rear speaker would have the A channel minus the B channel at a reduced amplitude, and the right rear speaker would have the B channel minus the A channel at a reduced amplitude. Thus the two rear speakers would have the same content except for being out of phase with each other. While the arrangement of FIG. 8 would not likely actually be employed in its exact extreme version, it well illustrates the manner in which the left front and right front channel speaker separations can be increased to any desired extent by designation of appropriate decoder output position angles.

Note that for greatly distorted position angle designations as in FIG. 8, some adjustment in signal levels is indicated. For example, the two rear speakers in FIG. 8 are reproducing rear center material so the volume should be decreased accordingly (or one speaker omitted).

It should further be noted that notwithstanding the current preference for placement of loudspeakers in the four corners of a room or studio so that their relationship to the listeners is left front, right front, left rear and right rear, it is perfectly feasible to arrange a four-directional system with speakers arranged in positions left, right, front and rear or in the centers of the walls of a listening room or studio. In such an arrangement, the position angles for both the input and output may correspond with the loudspeaker location and thus the position angles would be 0° , 90° , 180° and 270° . The encoding equations for such an arrangement are given in Equations 21 and 22 in the Appendix, and the decoding equations are given in Equations 23 through 26.

It will be noted that Equations 21 through 26 correspond to encoding and decoding equations in prior co-pending Scheiber patent applications.

It is obvious that numerous circuits other than those illustrated in FIGS. 2 and 3 can be used to provide the functions of the encoder and decoder. For example, suitable arrangements of operational amplifiers or transformers or combinations thereof may be used in either or both devices to provide the required functions. It is possible for a transformer type decoder to be located preceding or following the power amplifiers. In the latter case, only two power amplifiers are required for all four channels which means that existing stereo systems can be adapted merely by adding the decoder and two speakers at the receiving or playback station.

GAIN CONTROL APPARATUS

The separation between adjacent speakers provided by the encoder and decoder embodiments of FIGS. 2 and 3 alone provides the desired result, i.e. location of a virtual sound source at any place on a circle around a listener. However, to further emphasize the effect in respect to highly localized sound sources, it may be de-

sired to provide substantially unlimited separation between adjacent speakers for such highly localized sounds. This can be accomplished in a number of ways, some of which are of particular utility with the invention and, as such, may be considered to be an improvement over the basic system of FIGS. 1-4. Four such improvements are described below with reference to FIGS. 9, 10, 11 and 12.

FIG. 9 is a block diagram of a simplified form of a gain control circuit which varies the gain of any pair of "diagonal" channels (e.g. left front and right rear) with respect to the other diagonal channels. Hereinafter, by diagonal channels is meant the any pair of channels having an angular difference Δx substantially equal to 180° as defined electrically and algebraically with reference to FIG. 1 but not necessarily corresponding to the physical placement of the loudspeakers.

Since, in accordance with a basic embodiment of the invention, any given input will appear in three adjacent speaker channels with maximum gain in the speaker channel corresponding to the input channel, the directional effect can be emphasized by decreasing the gain of the two speakers on either side of the desired speaker. In the system of FIG. 1, these two diagonal speakers are also placed in physically diagonal positions. It can also be shown that where the absolute value of the LF signal is equal to the absolute value of the RR signal (i.e. the waveforms are identical except for possibly opposite polarity), the sound source should either be located at the right front or left rear speaker. Thus, when this condition exists it is desirable that the gain for the right front and left rear signals be maximum relative to the gain for the left front and right rear signals. Similarly, when either the RR or LF signal is zero or the waveforms in RR and LF are unrelated, the sound source should be located at the left front or right rear speaker, in which case the gain for the right front and left rear should be minimum relative to the gain of the left front and right rear signals.

The foregoing shows that the separation between the outputs of FIG. 1 (and thus the directional characteristics of the audio output) can be emphasized by simultaneously varying the gain in each pair of two diagonal outputs alternatively to controlling the gain in each of the individual channels. It is also desirable that the gain in one pair of diagonal channels be accompanied by an appropriate decrease in the gain of the other diagonal channels. Otherwise, an increase in gain (for example) to enhance the directional characteristic of a signal would result in a volume change of the total audio output as a function of direction. However, by simultaneously decreasing the power gain in one pair of diagonal channels (e.g. from 1 to 0) while increasing the power gain in the other diagonal channels (e.g. from 1 to 2), it is possible to maintain the total power at the speakers constant, and separation between adjacent speakers can be increased without changing the total volume of the system. These functions are performed by the systems illustrated in FIG. 9.

In FIG. 9, the decoder output is shown at the left. The four signals LF, RR, RF and LR are coupled to respective variable gain amplifiers 110LF, 110RR, 110RF and 110LR, which provide the signals for driving the four speakers as indicated. The LF and RR channels are also coupled directly through high-pass filters 112LF and 112RR to absolute value circuits 114LF and 114RR. The absolute value circuits 114 may comprise full-wave rectifi-

ers the outputs of which are of the same polarity. These signals, representing the absolute value of the LF and RR signals, are fed to respective logarithmic amplifiers 116LF and 116RR, which are well-known devices, providing output voltages approximately equal to the logarithm of the applied input voltage over the usable signal voltage range. The outputs of these amplifiers 116LF and 116RR are coupled through partial smoothing filters 117A and 117B to the negative and positive inputs, respectively, of an operational amplifier 118 which subtracts the two signals providing an output substantially dependent on $\log |LF| - \log |RR|$ (i.e. $\log |LF/RR|$). This signal is then fed through another absolute value circuit 120 and an averaging network 122 (an integrating circuit) to a gain control generator 123 which controls the gain of the two pairs of variable gain amplifiers 110LF, 110RR and 110RF, 110LR as a function of the output of amplifier 118.

As indicated above, where the absolute values of the LF and LR signals are equal, the gain of amplifiers 110RF and 110LR should be maximum and the gain of amplifiers 110LF and 110RR a minimum. When this condition exists, the output from the operational amplifier 118 will be equal to zero and the power gain of amplifiers 110RF and 110LR should be a maximum (e.g. two) while the gain of amplifiers 110LF and 110RR is a minimum (e.g. zero). At the other extreme, where either the RR or LF signal is equal to zero or the waveforms in RR and LF are unrelated, the output of the amplifier 118 will be a maximum (theoretically infinite but limited in practice to a definite value, for example, 9 volts). This maximum voltage causes the gain control generator 123 to provide output voltages which maximize the gain of amplifiers 110LF and 110RR and minimize the gain of amplifiers 110RF and 110LR.

For conditions between those described above, the gains of the respective pairs of amplifiers 110 will be appropriately controlled by generator 123. Mathematically, it can be shown (assuming a FIG. 4 embodiment of the system) that the curve of the required gain approximates a square root curve to yield constant total acoustical power output, with the gains in the respective diagonal channels being equal when the amplitude ratio of LF to RR (of RR to LF) is about 2.4 and the waveforms are the same. The equations 27 and 28 in the Appendix may be used to determine the (amplitude) gain control voltages from generator 123 where T is the time constant of the averaging circuit 122, K is a constant, t is time, V_{14} is the RF and LR control voltage and V_{23} is RF-LR control voltage.

One purpose of the high-pass filters 112A and 112B is to prevent the passage of low-frequency signals which might otherwise appear on the inputs to the variable gain amplifiers 110 and possibly modulate the amplifier inputs. It has further been found desirable to discriminate against lower frequency signals (at 6 dB per octave). The filters 112A and 112B also serve this function.

Filters 117A and 117B may have time constants from 100 to 1,000 microseconds and their outputs are in part responsive to the envelope of their inputs and in part responsive to instantaneous values. Each type of response is preferred in different situations and thus a desirable compromise is achieved by filters 117A and 117B. The averaging circuit 122 should respond to changes in the output of the amplifier 118 quickly enough so that the ear does not notice the delay, but

not so fast as to pass the actual waveform to the amplifiers 110. As an example, a 20 millisecond charging rate has been found satisfactory for practical purposes. to stabilize the action of the gain control circuits of the decoder, it may be desirable to mix slightly the LF and RR signals at the encoder output (or the left and right inputs to the encoder) to minimize excursions of the LF/RR signal ratio. Conversely, to prevent the log of this ratio from going to zero, constant phase differences may be introduced between the respective signals applied to the A and B channels at the encoder. This has the effect of restricting gain control action to a relatively narrow range so that the gain control action will not be audible at the speakers. Such mixing can be done in proportions which will accomplish the desired result without materially altering the audio characteristics. Where extreme channel separation is required, this technique would not be used.

As noted previously, there are many different ways of controlling the gain in the respective channels to provide the desired directional enhancement at the speakers. The embodiment illustrated and described with reference to FIG. 9 is a relatively inexpensive way of providing the desired gain.

FIG. 10 shows an alternative gain control arrangement in which the gain associated with each speaker is determined by a combination of a gain control element serially connected in the respective speaker input, and a gain control voltage generator whose output is coupled to the gain control element. The audio signal in each decoder output passes through the respective gain control element. Then, according to the output signal of the control voltage generator, the signal in the gain control element is either enhanced or attenuated. When the output signal of the control voltage generator is at a maximum, the output of the gain control element is at a maximum, and vice versa.

The gain control elements 203 and 204 are thus controlled by an output voltage V_1 produced by the control voltage generator 210. The gain control elements 208 and 206 are controlled by an output voltage V_2 produced by the control voltage generator 212. If desired, separate control voltage generators may be respectively coupled to each gain control element.

The expressions for each of the control voltages V_1 and V_2 are dictated by design considerations of the various control voltage generators which produce these expressions, as well as by the specific phase, waveform, and level cues present in the original signals A and B which are to activate the respective speakers.

For example, a desired acoustical reproduction requires that the gain associated with the speakers 31 and 34 increases as the ratio of the intensity levels of the signals g_1 and g_4 diverges from unity, or their waveforms become increasingly dissimilar. To achieve this result, the control voltage V_1 applied to the gain control elements 203 and 204 may be represented by one of various expressions.

V_1 may be proportional to the average absolute value of the logarithm of the quotient of the absolute values of g_1 and g_4 . Alternatively, V_1 may be proportional to the average absolute value of the logarithm of the quotient of the sum and difference of the absolute values of g_1 and g_4 . As a third alternative, V_1 may be proportional to the average of the quotient of the sum and difference of the absolute values of g_1 and g_4 . Equations 29-31 in the Appendix represent some expressions for

V_1 . In addition to the above or in combination with the above, similar expressions may be employed in which the envelopes of g_1 and g_4 are substituted for the instantaneous signals.

The gain for channels 32 and 33 must obviously be varied in a complementary manner to that of speakers 31 and 34 so that the voltage V_2 from control voltage generator 212 may be proportional to the constant minus the expression for the voltage V_1 . Control voltage V_1 increases as the loudness level associated with either the g_1 or g_4 signals becomes stronger with respect to the other, or their waveforms become increasingly dissimilar.

The gain for speakers 32 and 33, on the other hand, is to increase as the ratio of the intensity levels of each of the signals g_1 and g_4 approaches unity and as their waveforms become similar.

GAIN CONTROL SIGNAL APPARATUS

FIGS. 11 and 12 illustrate a further embodiment of a gain control system employing the basic principles of the invention wherein subsonic control tones are impressed upon the A and B channels for the purpose of controlling the gain of the two pairs of diagonal channels from the decoder 20. In describing the operation of FIGS. 11 and 12, the microphones, speakers, encoder and decoder perform the same function as previously described and therefore are not described further.

To facilitate an understanding of this embodiment it is convenient to refer to power ratios rather than voltage ratios as previously. The power which can be derived from a given signal is directly proportional to the square of the voltage level of that signal.

The signal recording means is illustrated in FIG. 11. The outputs of the right front and left rear microphones 2RF and 2LR are sensed and coupled to a power-adding circuit 130, while a similar power-adding circuit 131 sums the power outputs from microphones 2LF and 2RR. These two power-adding circuits are devices which produce output voltages directly proportional to the total power which can be derived from the applied input voltages. Their output voltages are then summed in an adding circuit 132, the output of which is thus proportional to the total power in the four input channels.

The outputs of summing circuits 130 and 132 are coupled to a ratio circuit 134 which, in turn, causes respective A and B modulators 136 and 138 to modulate a 20-cycle (or other subsonic) tone from oscillator 140. Ratio circuit 134 may be any of a number of well-known circuits and, for example, may produce a direct output voltage having an amplitude proportional to the ratio of the applied input voltages.

Modulators 136 and 138 may be adapted to amplitude-modulate the 20-cycle tone from oscillator 140 with respect to a preselected level, depending upon the magnitude of the applied control voltage from the ratio circuit 134. When the A modulator 136 provides a tone of increased amplitude, the B modulator 138 should be providing a tone of proportionately decreased amplitude. These modulated tones are then added to the A and B outputs of encoder 18 to provide the signals which are to be conveyed by the two-channel transmission path and which, in this particular embodiment, are indicated as A' and B'.

The receiving end of the system is illustrated in FIG. 12. Two high-pass filters 142 and 144 are used to separate the audio control tones from the A and B audio signals on the A' and B' channels. These A and B signals from the filters 142 and 144 are coupled to decoder 20 to provide the four output channels described above.

The control tones from the filters 142 and 144 are coupled to a gain control generator 146 which controls the gain of variable gain amplifiers 148RR, RF, LF and LR to increase the gain of one pair of diagonal channels while appropriately decreasing the gain of the other pair of diagonal channels. From the preceding discussion of FIG. 11, it follows that the amplitudes of the control tones will each be equal to the desired power in their corresponding diagonal input channels divided by the total power in the system. Each of these signals varies from a value of zero to one and their sum should always equal one. Accordingly, since the desired power ratios (i.e. the power ratios at the microphones) are directly represented in the control tone signals it is a simple matter for gain control generator 146 to utilize these known ratios to control the gain of amplifiers 148RR, LF and 148LR, RF to recreate the same ratios at the outputs of the amplifiers 148. This will necessarily enhance the desired signals while deemphasizing these signals which are not in their corresponding channels. The total power will also not be varied due to directionality changes. Generator 146 also serves as a normalizer to maintain the total gain of the four channels such that the sum of the power in the respective channels is maintained equal to a constant. This prevents unwanted changes in the amplitude of the control tone from affecting the volume of the outputs from the respective loud-speakers.

From the foregoing description of various embodiments of multidirectional sound systems in accordance with the invention, it will be seen that a highly effective system is provided capable of reproducing virtually all essential directional information without sacrificing fidelity, frequency response or other qualities of the audio information. Also transmission or recording is possible using only two conventional stereo channels. It should be appreciated that the particular apparatus disclosed is not intended to represent a suitable design for manufacturing economy but is rather presented for ease of explanation and to show the manner in which the system can be assembled from well-known existing electronic analog computer components and circuits. In practice, more economical transistor circuits would be substituted for the expensive operational amplifier components, the resistors also would be accorded much more tolerance in resistance values than indicated in the description, and other practical economies would be effected.

The gain control features described here are a useful adjunct to the system, but are not in all cases necessary. Furthermore, numerous other variations of gain control systems to enhance the separation between speakers or the localization of sound direction could be utilized other than the particular ones described here or in copending patent applications.

More elaborate gain control systems could utilize analysis circuits similar to the ones described herein but duplicated or triplicated so that each analysis circuit would serve to analyze a different frequency band within the overall audio frequency band of the system.

Gain controls for adjustment of the front to rear power ratio (rather than the diagonal pair power ratio)

are also potentially useful. Such adjustment can be made on the basis that inequalities between front and rear power should generally be increased to tend to restore the power ratios to those of the input signals.

In addition to those variations and modifications to the system described or suggested herein, numerous other variations and modifications will be apparent to those skilled in the art. The invention is to be understood not to be limited to the specific illustrations described and rather is to include those variations and modifications within the ordinary skill of the art.

APPENDIX

1. $A = f_1 \sin x_1/2 + f_2 \sin x_2/2 \dots + f_n \sin x_n/2$
2. $B = f_1 \cos x_1/2 + f_2 \cos x_2/2 \dots + f_n \cos x_n/2$
3. $g_n = A \sin x_n/2 + B \cos x_n/2$
4. $R1 = [R9/\sin(x_1/2)]$
5. $R2 = [R9/\sin(x_2/2)]$
6. $R3 = [R9/\sin(x_3/2)]$
7. $R4 = [1 + \sin(x_1/2) + \sin(x_2/2) + \sin(x_3/2) - \sin(x_4/2) \dots R10/\sin(x_4/2)]$
8. $R5 = [R11/\cos(x_1/2)]$
9. $R6 = [R11/\cos(x_2/2)]$
10. $R7 = [R11/-\cos(x_4/2)]$
11. $R8 = [1 + \cos(x_1/2) + \cos(x_2/2) + \cos(x_3/2) - \cos(x_4/2) \dots R12/-\cos(x_3/2)]$
12. $A = 0.9239f_1 + 0.3827f_2 + 0.9239f_3 - 0.3827f_4$
13. $B = 0.3827f_1 + 0.9239f_2 - 0.3827f_3 + 0.9239f_4$
14. $g1 = 0.9239A + 0.3827B$
15. $g2 = 0.3827A + 0.9239B$
16. $g3 = 0.9239A - 0.3827B$
17. $g4 = -0.3827A + 0.9239B$
18. $S_{dB} = 20 \log_{10} \cos(dx/2)$
19. $A = 0.9659f_1 + 0.2588f_2 + 0.8660f_3 - 0.5000f_4$
20. $B = 0.2588f_1 + 0.9659f_2 - 0.5000f_3 + 0.8660f_4$
21. $A = f_1 + 0.707f_3 + 0.707f_4$
22. $B = f_2 + 0.707f_3 - 0.707f_4$
23. $g1 = A$
24. $g2 = B$
25. $g3 = 0.707A + 0.707B$
26. $g4 = 0.707A - 0.707B$

$$V_{1,4} = K \sqrt{\int_{t-T}^t \left| \log \frac{LF}{RR} \right| dt} \quad (27)$$

$$V_{2,3} = K \sqrt{1 - \int_{t-T}^t \left| \log \frac{LF}{RR} \right| dt} \quad (28)$$

$$29. V_1 = K \log(G_1/G_4)$$

$$G_1 = g_1; G_4 = g_4$$

$$30. V_1 = K \log(G_1 - G_4 / G_1 + G_4)$$

$$31. V_1 = K \log(G_1 - G_4 / G_1 + G_4)$$

What is claimed is:

1. In a multidirectional sound system for encoding at least three directional input sound signals on A and B audio channels and reproducing from the A and B channels at least three directional output sound signals correlated with the input signals, encoder apparatus comprising at least three inputs for input sound signals having respective position angles associated therewith, first means for generating an A channel signal connected to at least three of said inputs, said first means

causing the amplitude of each said input sound signal in said A channel to be substantially proportional to the cosine of one half the angular difference between the input position angle and the angle assigned to the A channel, second means for generating a B channel signal connected to at least three of said inputs, said second means causing the amplitude of each said input sound signal in said B channel to be substantially proportional to the cosine of one half the angular difference between the input position angle and the angle assigned to the B channel, the angles assigned to said A and B channels differing by approximately 180 degrees, decoder apparatus comprising an A channel input and a B channel input, means for communicating said A channel and B channel signals to said decoder apparatus inputs, first, second and third means for generating first, second and third directional sound output signals each having a respective position angle associated therewith, each said means being connected to each of said A and B inputs and causing the amplitude of each of said A and B inputs in said output sound signal to be substantially proportional to the cosine of one half the angular difference between the output position angle and the angle assigned to the respective A or B input.

2. Apparatus as claimed in claim 1 wherein said A channel and B channel generating means cause the polarity of at least one of said input sound signals in said A channel to be opposite to its polarity in said B channel.

3. Apparatus as claimed in claim 1 wherein said first, second and third means for generating output signals cause at least one of said A and B channel signals in one of said outputs to be opposite to its polarity in at least one other of said outputs and the same as its polarity in at least another of said outputs.

4. Apparatus as claimed in claim 3 wherein said A channel and B channel generating means cause the polarity of at least one of said input sound signals in said A channel to be opposite to its polarity in said B channel.

5. In a multidirectional sound system for encoding at least three directional input sound signals on A and B audio channels and reproducing from the A and B channels at least three directional output sound signals correlated with the input signals, encoder apparatus comprising at least three inputs for input sound signals having respective position angles associated therewith, first means for generating an A channel signal connected to at least three of said inputs, said first means causing the amplitude of each said input sound signal in said A channel to be substantially proportional to the cosine of one half the angular difference between the input position angle and the angle assigned to the A channel, and second means for generating a B channel signal connected to at least three of said inputs, said second means causing the amplitude of each said input sound signal in said B channel to be substantially proportional to the cosine of one half the angular difference between the input position angle and the angle assigned to the B channel, the angles assigned to said A and B channels differing by approximately 180 degrees.

6. Apparatus as claimed in claim 5 wherein said A channel and B channel generating means cause the polarity of at least one of said input sound signals in said A channel to be opposite to its polarity in said B channel.

7. In a multidirectional sound system for encoding at least three directional input sound signals on A and B audio channels and reproducing from the A and B channels at least three directional output sound signals correlated with the input signals, decoder apparatus comprising an A input and a B input, at least three directional sound signal outputs, first, second and third means for generating first, second and third directional sound output signals each having a respective position angle associated therewith, each said means being connected to each said input and causing the amplitude of each said input in said output sound signal to be substantially proportional to the cosine of one half the angular difference between the output position angle and the angle assigned to the respective A or B input, the angles assigned to said A and B inputs differing by approximately 180 degrees.

8. Apparatus as claimed in claim 7 wherein said first, second and third means for generating output signals cause at least one of said A and B channel signals in one of said outputs to be opposite to its polarity in at least one other of said outputs and the same as its polarity in at least another of said outputs.

9. In a multidirectional sound system for encoding at least three directional input sound signals on A and B audio channels and reproducing from the A and B channels four directional output sound signals correlated with the input signals, decoder apparatus comprising an A input and a B input, first, second, third and fourth means for generating first, second, third and fourth directional sound output signals each having a respective position angle associated therewith, at least three of said means being connected to each said input and causing the amplitude of each said input in said output sound signal to be substantially proportional to the cosine of one half the angular difference between the output position angle and the angle assigned to the respective A or B input, the angles assigned to said A and B inputs differing by approximately 180 degrees.

10. In a multidirectional sound system for encoding at least three directional input sound signals on A and B audio channels and reproducing from the A and B channels four directional output sound signals correlated with the input signals, decoder apparatus comprising an A input and a B input, first, second, third and fourth means for generating first, second, third and fourth directional sound output signals each having a respective position angle associated therewith, each said means being connected to each said input and causing the amplitude of each said input in said output sound signal to be substantially proportional to the cosine of one half the angular difference between the output position angle and the angle assigned to the respective A or B input, the angles assigned to said A and B inputs differing by approximately 180 degrees.

11. In a multidirectional sound system for encoding at least three directional input sound signals on A and B audio channels and reproducing from the A and B channels four directional output sound signals correlated with the input signals, decoder apparatus comprising an A input and a B input, first, second, third and fourth means for generating first, second, third and fourth directional sound output signals, each having a respective position angle associated therewith, each said means being connected to each said input and causing the amplitude of each said input in said output sound signal to be substantially proportional to a func-

tion of the angular difference between the output position angle and the angle assigned to the respective A or B input.

12. In a multidirectional sound system for encoding at least four directional input sound signals on A and B audio channels and reproducing from the A and B channels at least four directional output sound signals correlated with the input signals, decoder apparatus comprising an A input and a B input, at least four directional sound signal outputs, first, second, third and fourth means coupled to said A and B inputs for generating first, second, third and fourth directional sound output signals each having a respective position angle associated therewith, each said means causing the amplitude of each said input in said output sound signal to be substantially proportional to the cosine of one half the angular difference between the output position angle and the angle assigned to the respective A or B input, the angles assigned to said A and B inputs differing by approximately 180°.

13. Apparatus as claimed in claim 12 wherein said

first, second, third and fourth means for generating output signals cause at least one of said A and B channel signals in one of said outputs to be opposite to its polarity in at least one other of said outputs and the same as its polarity in at least another of said outputs.

14. In a multidirectional sound system for encoding at least three directional input sound signals on A and B audio channels and reproducing from the A and B channels four directional output sound signals correlated with the input signals, decoder apparatus comprising an A input and a B input, first, second, third and fourth means coupled to said A and B inputs for generating first, second, third and fourth directional sound output signals each having a respective position angle associated therewith, each said means causing the amplitude of each said input in said output sound signal to be substantially proportional to a function of the angular difference between the output position angle and the angle assigned to the respective A or B input.

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UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,746,792 Dated June 17, 1973

Inventor(s) PETER SCHEIBER

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

On the cover sheet insert -- The portion of the term of this patent subsequent to Jan. 4, 1989, has been disclaimed. -- .

Signed and sealed this 21st day of January 1975.

(SEAL)
Attest:

McCOY M. GIBSON JR.
Attesting Officer

C. MARSHALL DANN
Commissioner of Patents