Nov. 24, 1964 M. CAMRAS 3,158,695

STEREOPHONIC SYSTEM

Filed July 5, 1960 2 Sheets-Sheet 1

Fig-1

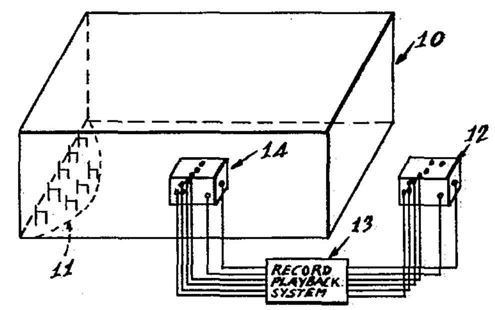


Fig-4

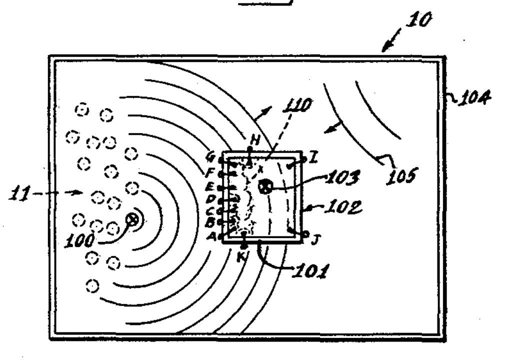


Fig-2

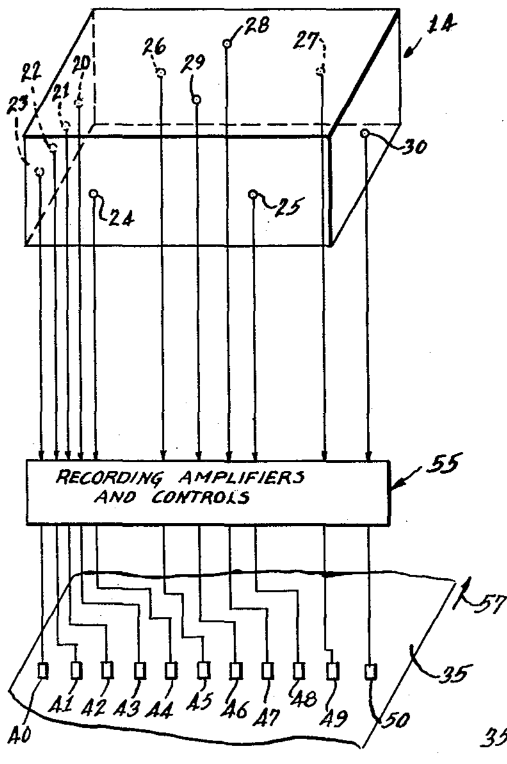
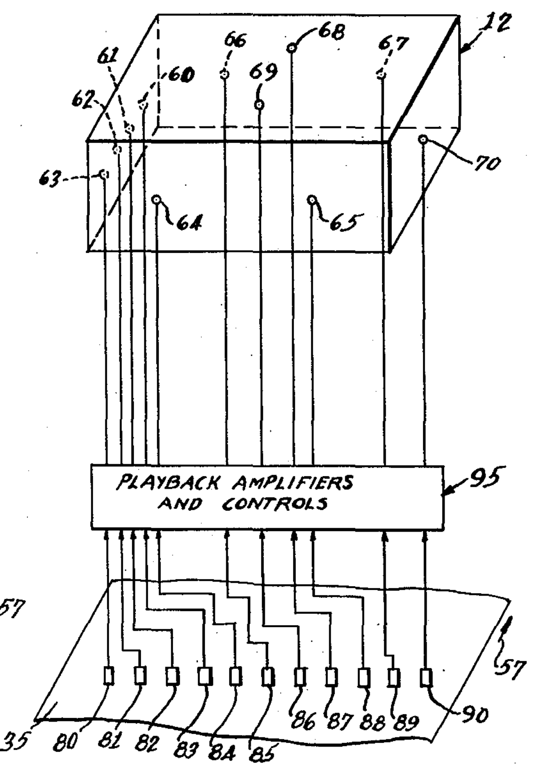


Fig-3



INVENTOR.
Marvin Camras

BY

Hill, Sherman, Meroni, Gross & Simpson

Attys.

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Fig. 5

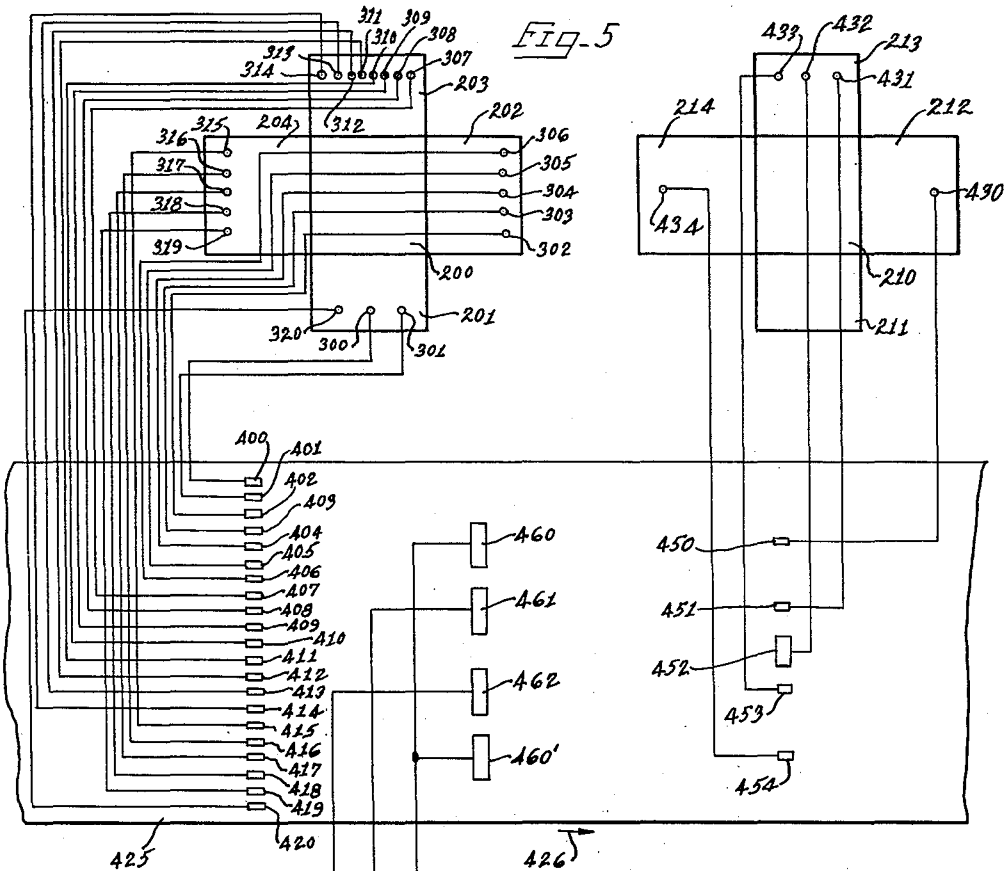


Fig. 6

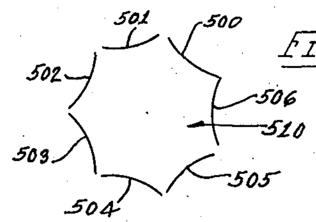


Fig. 7

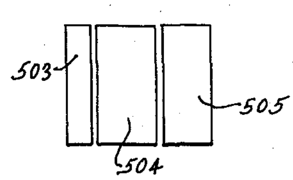
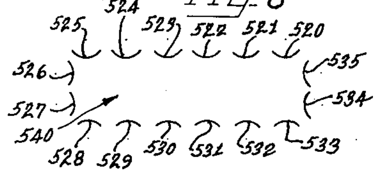


Fig. 8



Inventor
Marvin Camras

by Hill, Sherman, Meroni, Gross & Simpson Attys.

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STEREOPHONIC SYSTEM

Marvin Camras, Glencoe, Ill., assignor to IIT Research Institute, a corporation of Illinois

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4 Claims. (Cl. 179—100.1)

This invention relates to a stereophonic system and method and particularly to a system for reproducing the sound field of a concert hall or the like in a small volume such as the average living room.

It has been considered that "perfect fidelity" of sound reproduction would be achieved if the exact sound pressure in the ears of an on-the-spot listener could be re-created at a different place or time. A two channel binaural system with earphones approaches this ideal, but experience with binaural reproduction indicates an additional requirement for "perfect fidelity," namely that when the listener moves while hearing the reproduction, the sound pressure in his ears changes in the same manner as if he were a direct observer.

When the latter requirement is not fulfilled, the room "turns" when the binaural listener turns his head, and the sound always seems to come from behind him, and never from the front hemisphere. The difference between direct observation and listening through earphones may result in part from subtle modifications caused by the external ear shape which may occur during direct listening but not when earphones are worn. Thus, during the recording of sound for binaural reproduction, the microphones should be associated with dummy ears of the same dimensions as those of the listener. Besides the dependence of apparent sound location on the position of the head, other objections to headphones are that they are inconvenient, uncomfortable and anti-social.

To avoid the disadvantages of earphones, stereophonic sound was devised using two or more loudspeakers each with its own channel. Pickup microphones are generally spaced the same distance as the speakers, 6 to 30 feet apart or more, in contrast to the seven inch spacing of binaural microphones. Stereophonic sound gives fair to excellent results, depending on program material and acoustic techniques, but is disappointing compared to binaural sound with earphones. It is easy to show that stereophonic sound does not maintain the correct phase relation between sounds that reach the ears. In fact the phase relations are hopelessly confused even when an observer stands equidistant between both speakers. Loudness alone is used for localizing the sound, and while this can be fairly accurate in tests, it does not give the conviction of reality that is felt when both loudness and phase are correct.

In the present invention, it is possible to re-create the original sound field for example in a smaller room such as an ordinary living room. The listener can then move freely within wide boundaries and experience the same sound sensation as in the original location, with loudness, phase and other relations being correct.

It is therefore an object of the present invention to provide a novel and improved stereophonic sound recording and reproducing system and method.

It is another object of the present invention to provide a system and method for recording and reproducing the sound field of a relatively large volume within a substantially smaller volume with maximum realism.

Another object of the present invention is to provide a multi-channel sound record capable of producing maximum realism of reproduction of sound which has been recorded in a relatively large volume and is to be played back in a relatively smaller volume.

Other objects, features and advantages of the present invention will be apparent from the following detailed

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description, taken in connection with the accompanying drawings, in which:

FIGURE 1 is a diagrammatic illustration of the overall sound recording and reproducing system in accordance with the present invention;

FIGURE 2 is a diagrammatic view illustrating the principles of the present invention in connection with the recording operation;

FIGURE 3 illustrates a preferred playback system;

FIGURE 4 is a diagrammatic representation of the concept of the present invention;

FIGURE 5 is a diagrammatic illustration of a recording and two reproducing systems embodying further concepts of the present invention;

FIGURE 6 is a diagrammatic top plan view showing vertically elongated loudspeaker units about a playback volume;

FIGURE 7 is a diagrammatic side elevational view of the arrangement of FIGURE 6; and

FIGURE 8 is a diagrammatic top plan view of a second arrangement of vertically elongated loudspeaker units about a playback volume.

As shown on the drawings:

FIGURE 1 illustrates a relatively large volume **10** such as a concert hall wherein a musical program is to be originally produced by means of a sound source such as an orchestra located at **11**. The sound is to be electrically reproduced through the medium of a record-playback system **13** in a substantially smaller volume such as an ordinary living room indicated at **12**. In accordance with the present invention, a smaller recording volume indicated at **14** is located at a preferred listening area within the larger volume **10**. The volume **14** is defined by directional microphones such as indicated at **20**, **21**, **22** and **23** at the front face of the volume **14** directly facing the sound source **11**, by means of microphones **24** and **25**, and **26** and **27** located at the sides of the volume **14**, by means of microphones **28** and **29** located at the top side of the volume and by means of a microphone **30** located at the rear side of the volume **14**. Each of the microphones preferably has its most sensitive face directed outwardly from the volume **14** so that sound waves entering the volume **14** will be picked up readily by the outward directionality of the microphones. Sound waves leaving the volume **14** will be picked up only weakly because the directionality of the microphones discriminates against them. This can be enhanced by enclosing the volume **14** with walls of acoustic material for absorbing sound waves impinging thereon. The enclosing walls of the volume can be made of material having the acoustic impedance of free space, so as to cause a minimum disturbance of the sound field. Alternatively if the microphones are sufficiently insensitive to sound waves traveling outwardly from the volume, the microphones can be mounted on a frame of thin tubing which does not disturb the sound field impinging thereon.

As indicated in FIGURE 2, the output of each microphone may be recorded on a separate channel of a recording medium **35** by means of a series of recording devices **40–50** with suitable individual amplification and control interposed as indicated by the component **55** labeled recording amplifiers and controls. After recording of a musical selection on the record medium **35**, which may for example be a suitable magnetic recording tape moving at uniform speed in the direction of the arrow **57**, the medium may be rewound onto a supply spool and utilized as a master record from which duplicate records may be manufactured for sale to the public and subsequent reproduction in ordinary living rooms such as indicated at **12** in FIGURE 3.

The listening volume **12** may be of substantially the same dimensions as the volume **14** and may have loudspeakers **60–70** located in correspondence with the location of microphones **20–30** with respect to the volume **14**. Playback of tape **35** is accomplished by heads **80–90** coupled to the respective corresponding loudspeakers **60–70** by playback amplifiers and controls component **95**. The loudspeakers **60–70** are suitably mounted at the interior of the volume **12** and are directed inwardly so as to set up substantially the same sound field within the volume **12** as would have been set up within the volume **14**. Thus a listener within the volume **12** experiences substantially the same sound sensations as would have been experienced by a direct listener located within the volume **14** of the original larger volume such as concert hall **10**. The boundaries of the volume **12** are preferably of sound absorbent material for minimizing reverberation effects within the volume **12**.

FIGURE 4 illustrates the concept of the present invention by illustrating directional microphones A, B, C, D, E, F, G, H, I, H and K directly coupled to inwardly directed loudspeakers to form microphone-speaker pairs disposed about a volume **102**. As illustrated, a sound wave emanating from an apparent source **100** is effectively transmitted through the sound impervious walls **101** of the volume **102** to recreate a sound wave pattern within the volume **102** and at the location **103** of the listener which is substantially identical to the sound wave pattern which would exist at the location **103** in the absence of the walls **101**. Sound waves reflected by the walls **104** and ceiling of the larger volume **10**, such as the reflected wave indicated at **105**, will also be transmitted into the enclosed volume **102** by means of the microphone-speaker pairs. In the diagrammatic illustration of FIGURE 4, the connecting lines between the correspondingly located microphones and speakers may be thought of as representing suitable amplifier channels and the like as illustrated in detail in FIGURES 2 and 3.

Describing FIGURE 4 in greater detail, a wave front from a source such as indicated at **100** strikes each microphone at a slightly different time. After being relayed by corresponding loudspeakers, the wave fronts such as indicated at **110** inside the smaller room **102** combine by Huygen's principle to give a reproduced wave front of the same curvature as that which would have been produced at the listening position **103** if the direct wave from source **100** had not been interrupted. Thus the listener at location **103** will have a true sensation of the sound from source **100**. Similarly, all other sounds in the large room **10** including reverberations will come from their correct directions.

A practical embodiment in accordance with FIGURES 1 to 3 utilized a twelve channel system with seven channels for the front wall of the recording volume **14**, one for each side wall, two for the back wall and one for the top wall. It is preferred that the sources at the side, back and top walls be made of substantially broader area. Microphones used were Shure Brothers 1737A Monoplex directional type. The loudspeakers were of eight inch size mounted in four foot baffles. The array was fitted for an approximately ten foot square listening space.

By way of further explanation of the advantages of the present system over a conventional stereophonic system, a discussion of the mechanism by which a listener senses direction is presented herebelow.

When a listener attends to a sound originating directly in front of him, both ears receive the same impulse. If the sound is slightly to one side of the listener and in front of him, the farther ear hears the sound a fraction of a millisecond after the closer ear, and the short delay in the sound reaching the farther ear enables the listener to sense the direction from which the sound emanates even though the loudness of the sound at each ear is practically the same. Sounds which are farther off-center undergo additional delay at the farther ear, which is sensed by the listener providing the delay is not more than a millisecond. In addition to sensing delay time, the listener is able to sense a difference in "frequency response" resulting from the shading by the head of the impinging sound waves which shading causes the higher frequencies to be progressively attenuated in the ear farthest from the sound source. At the highest frequencies the external parts of the ear have a shading effect which varies with the listening angle and may be responsible for locating the source with respect to the front or back of the listener.

It will be understood that phase differences at frequencies from 3,000 to 15,000 cycles per second (corresponding to wavelengths in air of approximately four inches to three-fourths of an inch) may give several wavelengths of phase difference between one ear and the other; thus, the mechanism of directional perception must depend on loudness differences due to shading of the head and outer ear. At frequencies of 1000 cycles per second the wavelengths are about one foot long, comparable to the path length between ears, and perception of phase differences is most marked. Low frequency components of one hundred cycles per second are of about ten foot wavelengths, and loudness and phase are nearly equal in both ears. As a consequence, at low frequencies it might be expected that it would be possible to utilize a single "woofer" loudspeaker receiving sound from all of the directional microphones of the present invention. It has been found preferable, however, to provide a multiple arrangement of speakers at low frequencies as well as at higher frequencies, as will be discussed later herein.

It is important to note that for any given sound frequency, if the tone is interrupted or varied, the time of arrival of the transient at the respective ears of the listener gives the sense of directionality. If multiple sources are used, an interesting result obtains, namely; (1) when the same sound comes from both sources, but the sound from one source is delayed from one millisecond to about 50 milliseconds, the listener hears only one sound which seems to come from the source first heard; (2) when the delay is more than about 50 milliseconds, the sound second heard appears as a distinct echo; (3) when the delay is less than a millisecond, the listener hears one sound which seems to come from between the sources, being close to the center if the delay is less than about ⅓ millisecond, and approaching the source of least delay if the time difference is increased to one millisecond.

If the second (delayed) source is made louder than the first source, time delays up to one millisecond can be compensated. Increasing the loudness of the second (delayed) source 10 decibels approximately compensates for a one millisecond delay. For delays of from one to 30 milliseconds, the sounds seem to arrive simultaneously if the second (delayed) source is ten decibels louder than the first source; above 30 milliseconds delay, less than a 10 decibel increase in the sound from the second source is effective to compensate for the delay. At about a 50 millisecond delay between the sources, we hear the second source even if the volume of the second source is the same as the volume of the first source.

While it was believed that the bass components would be sufficiently non-directional so that a single source would be adequate, especially if delayed a few milliseconds with respect to the treble sources, under test conditions, low frequency sounds were localized much better than expected even when transient conditions were minimized, and even when the bass channel was delayed by amounts ranging from ½ to 10 milliseconds. It was expected that the undelayed channel would "take over" but this was not the case where there was a wide spectrum of sound frequencies. At least two bass speakers are considered necessary at the front of the listening area. A preferred solution, however, is to have wide range good quality speakers in each channel.

The inadequacy of ordinary stereophonic reproduction is apparent when it is considered that both ears of the listener hear both sources and that delay times are invariably many milliseconds, compared to the maximum of less than one millisecond between the respective ears of the listener that can occur in nature. As a result, one speaker at a time predominates, with the other (or others) adding confusion. On the other hand, the system of the present invention provides a very good illusion, with no impression that sound comes from any one speaker.

In summary, it may be stated that experimental results indicate the following conclusions for the system of the present invention:

(1) A sound level distribution approximately that in the original space can be recreated with the system of the present invention.

(2) Subjectively, reproduction by the system of the present invention gives one the feeling of being in a large indoor room, even when reproduced outdoors or in an acoustically dead space. Under the same conditions, single channel or ordinary stereo fails to give this impression.

(3) A single source for low frequencies has not proved adequate, and it is preferred to utilize wide range good quality speakers in each channel.

(4) Calculations indicate that the maximum distance that loudspeakers or microphones can be separated without producing a discontinuous or jump effect as the source or listener moves from side to side is about 30 inches for average living room conditions. It is the angular relationship between source and successive microphones, or listener and successive loudspeakers which actually determines whether the discontinuous effect will occur, rather than the physical separation between microphones or loudspeaker per se. Where both the performers and the audience are in relatively fixed positions these requirements may be relaxed.

The multiple sources of this system may in some cases add liveness to the overall result. This is readily compensated by decreased reverberation, preferably in the recording environment. The compensation by decreased reverberation may also take place in the playback room, if desired, or both in the recording environment and in the playback environment. Instead of regular symmetrical placement of microphones and speakers, irregular spacing both in the horizontal direction and in the vertical direction is advantageous to avoid periodic effects or harshness such as may be experienced from a uniformly spaced array. It is believed unnecessary to illustrate such irregular spacing in the drawings, but by way of example with respect to FIGURE 2, microphones **20** and **23** may be spaced approximately one foot above the level of microphones **21** and **22**, and the spacing between microphones **21** and **22** may be six inches greater in the horizontal direction than the spacing between microphones **22** and **23** and **21** and **20**. Similarly, microphones **25** and **27** may be located approximately one foot vertically above the level of microphones **24** and **26**. The loudspeakers in FIGURE 3 would be irregularly spaced in the same way as described for the respective corresponding microphones. Fewer microphones and speakers may be used at the rear of the volume than facing the front as is illustrated in FIGURES 2 and 3.

In an economy system the accuracy and location of the original source of sound may be sacrificed somewhat, particularly since precision of location is not as important as the creation of a good illusion, with a sense of realism and conviction that the original image is actually present adjacent the playback volume.

Instead of a full complement of recorded channels and separate electrical lines, the original input signals from the array of microphones may be successively sampled and recorded on a lesser number of channels on the tape in predetermined sequence, the reproduced signals from the successive heads cooperating with the successive channels being sampled in the corresponding sequence and coupled to the corresponding loudspeakers in sequence.

As a further example, sound signals from a plurality of microphones may be recorded on a single channel as modulation of suitable carrier signals by non-interfering frequency bands. On playback, the recorded carriers would be segregated and demodulated to supply the original signals to the corresponding respective loudspeakers of the playback volume. A moving microphone or microphones and a corresponding moving loudspeaker or corresponding moving loudspeakers may be used instead of stationary ones to cover a larger area. For example, microphones **24, 25, 26, 27** and **30** in FIGURE 2 and the corresponding loudspeakers **64, 65, 66, 67** and **70** in FIGURE 3 may oscillate in unison over predetermined arcs and at comparable rates in FIGURES 2 and 3.

In the useful listening area, it is preferable that a sound, as reproduced from the nearest adjacent speakers should not differ by more than a millisecond at the ears of the listener. In other words, any error should be limited to less than a millisecond as experienced by the listener. This will always be the case if the reproducers (and corresponding microphones) are one foot apart or less, but the distance between adjacent microphones and loudspeakers can be greater if the listening area is restricted, for example.

FIGURE 5 illustrates a further important concept of the invention. The rectangles **200–204** represent the top, rear, right, front and left walls, respectively, of a recording volume such as the volume indicated at **14** in FIGURE 1, while the reference numerals **210–214** and **220–224** represent the corresponding walls of respective playback volumes. While a volumetric array of acoustic transducers is considered essential to the optimum realism and fidelity of reproduction, in FIGURE 5 the transducers have been illustrated as lying in a common horizontal plane since useful, though inferior, results are obtained by such an arrangement. The acoustic transducers associated with the recording volume **200–204** have been numbered **300–320** and are coupled by suitable means such as the recording amplifiers and controls component **55** in FIGURE 2 to respective recording devices **400–420**. In accordance with one concept illustrated in FIGURE 5, signals from adjacent acoustic transducers of a predetermined group are recorded in adjacent channels on the record medium **425** which travels, indicated by arrow **426**. A lesser number of loudspeakers **430–434** are shown associated with the playback volume **210–214**, and a still lesser number of loudspeakers **440, 441** and **442** are illustrated associated with the playback volume **220–224**. It will be observed that because of the fact that the signals on adjacent channels correspond to spacially adjacent microphones of the recording volume **200–204**, a single loudspeaker may receive signals from a number of recorded channels by means of a single reproducing device scanning said channels on the tape or other record medium **425**. Thus the single reproducer device **452** which may be a magnetic playback head having a longitudinal gap of width to extend continuously across two channels of the record medium **425** may be connected to the loudspeaker **432** through a suitable playback amplifier and controls component such as indicated at **95** in FIGURE 3. Loudspeaker **432** will then produce a sound pattern which represents a combination of the sound patterns received by microphones **310** and **311** at the front wall **203** of the recording volume **200–204**. It will, of course, be understood that normally a master tape is recorded by means of the recording devices **400–420** and the separate duplicate tapes are produced from the master tape for playback by the playback transducers such as **450–454**. For convenience of illustration in FIGURE 5, however, only a single record tape **425** is illustrated. The playback device **452** thus scans the channels recorded by recorder devices **410** and **411** and may, for example, simple superimpose the two recorded signals to provide a single output to the loudspeaker **432**. The playback devices **450, 451, 453** and **454** have been illustrated as scanning channels recorded by heads **404**, **408**, **413** and **417**, respectively, which have signals corresponding to the sound impinging upon microphones **304**, **308**, **313** and **317**, respectively.

The same master recording tape may be utilized in an even more economical playback system represented by the playback volume **220–224** and loudspeakers **440–442**. In this case playback devices **460** and **460′** are suitably connected to loudspeaker **440** with the playback amplifiers and controls component interposed as indicated at **95** in FIGURE 3. The playback devices **460** and **460′** may scan the channels recorded by recording devices **403**, **404**, **405**, **416**, **417** and **418** corresponding to the sound signals received by microphones **203**, **204**, **205**, **216**, **217** and **218** in the volume **200–204**. Similarly, playback device **461** may scan channels recorded by recording heads **407**, **408** and **409** and playback device **462** may scan channels recorded by heads **412**, **413** and **414**.

Thus, a tape record may be made with a large number of channels, so that it inherently contains information for the highest quality of reproduction. Since the expense during recording is not of great importance where the record made is to be sold in large quantities, the additional complexity of the large number of microphones and recording channels is justified. The highest quality record can be duplicated as readily by contact printing as one with fewer channels. As illustrated in FIGURE 5, during reproduction, the number and location of playback heads cooperating with the record tape is made to correspond with the loudspeaker array used, and with their location. Fewer playback heads may thus be used than recorded channels, and some playback heads may straddle several channels. This makes possible playback systems varying from the highest quality to ones as economical as desired while requiring only a single recording operation and a single master tape. Maximum adaptability, of course, requires that the signals recorded on successive adjacent channels correspond to the instantaneous sound signals at successive adjacent microphones. If desired, heads as **452** may pick up only one channel instead of several, and such heads may be made movable or adjustable laterally to give different space effects, or to allow optimum setting for different rooms. For example, different sets of microphones may be located to define respective recording volumes of respective different sizes to correspond to different sizes of playback rooms. The signals from several sets of microphones may be recorded on predetermined sets of channels on a single tape so a particular user of the tape can select the set of channels for playback which are correct for the size of playback room and speaker array to be employed.

In each of the illustrated embodiments, the loudspeakers may be of the electrostatic type covering an appreciable extent in the vertical direction, for example the entire height of a living room, so that the signal does not alter with the height location of the listener's ears. Convex vertically elongated speaker units such as illustrated at **520–535** about the playback volume **540** are examples of the use of such units. By way of example, a vertical array of microphones could be arranged with respect to a recording volume to correspond to each of the vertically elongated speaker units **500–506** or **520–535**. Flat panel type loudspeaker units may also be used. The vertically elongated speaker units may fit against the walls of the playback volume and can be made part of the decoration of the playback room. In place of a long electrotype loudspeaker units may also be used. The vertically static panel, a vertical array of electromagnetic speakers can be used, or vertically elongated panels can be used having a central vertical slit with speakers in a vertical array behind the slits.

The successive adjacent microphones such as **20–23** in FIGURE 2 are spaced apart a distance corresponding to a maximum time delay between sound waves from source **11**, FIGURE 1, reaching respective adjacent microphones of less than one millisecond so as to prevent a total delay of more than one millisecond in sounds reaching the listener, for example as indicated at **103** in FIGURE 4, from a source such as indicated at **100** via adjacent microphone loudspeaker pairs. Thus, the spacing of adjacent microphones such as **20–23** and the spacing of the corresponding loudspeakers such as **60–63** in FIGURE 3 in such that an impulse in the original environment, for example from source **11** in FIGURE 1, will be transmitted via microphones **20–23** and the tape to loudspeakers **60–63** as a succession of impulses which do not differ by more than a millisecond from each other in the listening volume such as indicated at **12** in FIGURE 3.

It will be aparent that many further modifications and variations may be made without departing from the scope of the novel concepts of the present invention.

I claim as my invention:

1. Apparatus for transducing a time varying acoustic field from a larger volume to a smaller volume displaced from said larger volume comprising a volumetric array of microphones disposed about four sides of and above a pick-up volume within said larger volume and substantially corresponding to the dimensions of said smaller volume, said microphones all being directed outwardly of said pick-up volume with the microphones being sensitive to sound waves impinging upon said pick-up volume from the exterior thereof but being relatively insensitive to any sound waves within the pick-up volume which tend to impinge on the microphones, a volumetric array of loudspeakers arranged in said smaller volume substantially in spacial correspondence to corresponding microphones of said pick-up volume, and means for transmitting the output of each microphone of said pick-up volume to the corresponding loudspeaker of said smaller volume for recreating in said smaller volume substantially the acoustic field which would have been effectively perceived by a listener in the pick-up volume of said larger volume.

2. A sound reproduction system comprising a record capable of reproducing a time varying acoustic event as experienced within a larger volume within a smaller volume of floor area of the order of 100 square feet comprising a multi-channel record medium having signals recorded on the respective channels related to the acoustic event but differing in phase and intensity to represent the acoustic sensing of the event at a volumetric array of points about a recording volume within said larger volume and generally corresponding in dimensions to said smaller volume, an array of loudspeakers about said smaller volume of floor area of the order of 100 square feet corresponding in position to said volumetric array of points, and multi-channel reproducing means for reproducing the signals from the respective channels of the record medium and for energizing respective corresponding ones of said loudspeakers to reproduce said time varying acoustic event in said smaller volume.

3. A sound reproduction system comprising a record capable of reproducing a time varying acoustic event as experienced within a larger volume within a smaller rectilinear volume having a wall at one side thereof comprising a multi-channel record medium having signals recorded on the respective channels related to the acoustic event but differing in phase and intensity to represent the acoustic sensing of the event at a rectilinear volumetric array of points about a rectilinear recording volume within said larger volume and generally corresponding in dimensions to said smaller rectilinear volume, an array of loudspeakers about said smaller rectilinear volume corresponding in position to said volumetric array of points, and multi-channel reproducing means for reproducing the signals from the respective channels of the record medium and for energizing respective corresponding ones of said loudspeakers to reproduce said time varying acoustic event in said smaller

volume, said array of loudspeakers including a series of loudspeakers along said wall of said smaller rectilinear volume having a spacing therebetween not greater than about 30 inches to accommodate recombination of the sound emanating therefrom by Huygen's principle.

4. Apparatus for transducing a time varying acoustic field from a larger volume to a smaller volume of floor area of the order of 100 square feet displaced from said larger volume comprising a rectilinear volumetric array of microphones disposed about a pick-up volume having a floor area of the order of 100 square feet within said larger volume and substantially corresponding to the dimensions of said smaller volume, a volumetric array of loudspeakers arranged in said smaller volume substantially in spacial correspondence to corresponding microphones of said pick-up volume, and means for transmitting the output of each microphone of said pick-up volume to the corresponding loudspeaker of said smaller volume for recreating in said smaller volume substantially the acoustic field which would have been effectively perceived by a listener in the pick-up volume of said larger volume, said microphones and loudspeakers associated with the pick-up volume and said smaller volume respectively having a spacing therebetween corresponding to a maximum time delay between the sound waves reaching the listener in the smaller volume from adjacent loudspeakers of not more than one millisecond.

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