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METHOD FOR SYNTHESIZING AUDITORIUM SOUND

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FIG. 1.

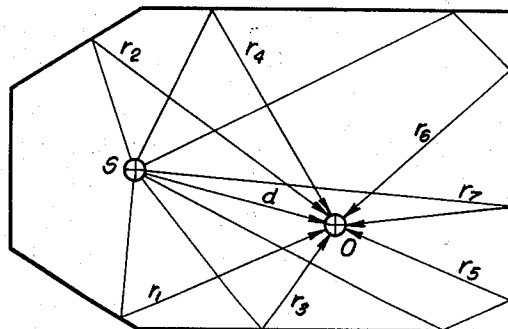
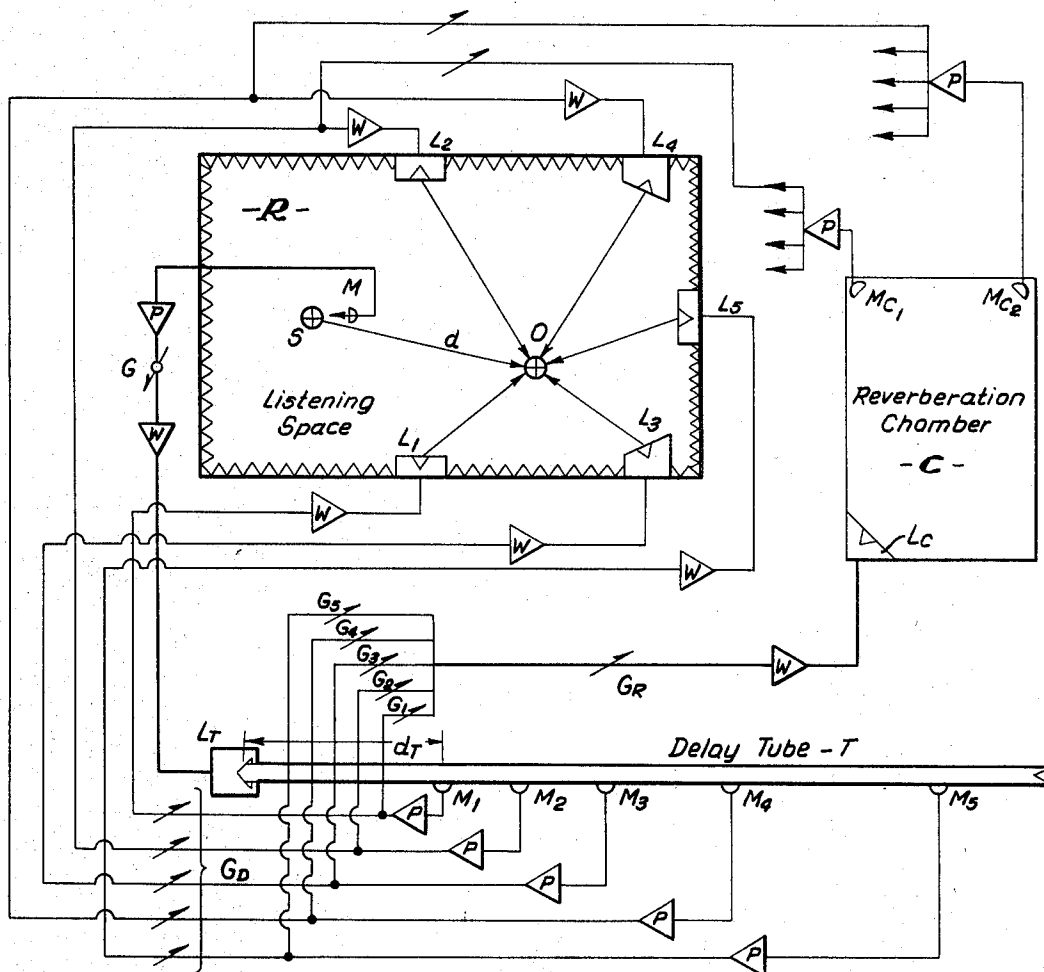


FIG. 2.



W - POWER AMPLIFIER
P - PREAMPLIFIER
G - GAIN CONTROL

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**METHOD FOR SYNTHESIZING AUDITORIUM
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20 Claims

ABSTRACT OF THE DISCLOSURE

The invention contemplates synthesizing sound for relatively small room listening, as produced in an auditorium where sound created at a stage location is transmitted directly to a listener location and indirectly by side wall reflections and by reverberation. According to the invention, provision is made for (1) transmitting program sound from a first location in a listening room directly to a listener location therein, (2) subjecting energy productive of the program direct sound to progressively extended delay beyond the time of the direct sound transmission and selecting and transmitting into the room atmosphere increments of the delayed energy as delayed sounds simulative of auditorium side wall reflected sounds and (3) subjecting sequential increments of the delayed energy to reverberation and transmitting the accumulated reverberated energy as sound into the room atmosphere. The invention particularly contemplates and provides for relative variation in magnitudes of the delayed energy increments in advance of their reverberation.

**BACKGROUND AND CHARACTERIZATION OF
THE INVENTION**

This invention has to do generally with augmenting of sounds produced and heard in relatively small rooms or larger non-reverberant studios, with the objective of simulating sound effects experienced by a listener in an auditorium or theater designed and constructed to create good or superior acoustical effects.

The present invention provides for simulation of sound production in acoustically well designed auditoriums, so effectively that in a relatively small home room or studio the listener's sound experience may closely approach that of large auditorium or concert hall listening.

It is now known that successes in the acoustical design of auditoriums can be achieved by carefully adjusting the configurations and relations of surrounding surfaces so as to present to members of the audience, direct and reflected sound transmissions which are controlled in regard to the directions and relative times of arrival to the listener. Such principles of auditorium design are now established to the extent that desirable acoustical properties and effects may be predetermined by acoustical model testing during design and in advance of actual construction. For purposes of the present invention it is most desirable that its processes of sound "syntheses" shall be predicated upon the performance characteristics of a known or acoustically predetermined auditorium of excellent acoustical quality, instead of the artificial process of attempting random selections and combinations of sound relationships. Accordingly, it is contemplated that the basis for synthesis may be preconceived by using as a model an actual auditorium acoustical design or configuration.

The experience of good concert hall sound results from the series of acoustical events occurring within a period of time of only about 0.2 second. There are three essential auditory factors associated with good sound in an auditorium. The sound arriving at the listener's position directly from the sound source, whether real or reproduced by

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loudspeaker, (or that additional sound reflected from an overhead surface or "canopy" within a very short time interval) is called the direct sound. This direct sound contributes the property of clarity to musical sounds or intelligibility to speech sounds or lyrics. In a good hall the early reflections of sound arrive at the auditor from many directions before or in the process of becoming reverberant. Thus early reflected sound should produce for the listener a feeling of envelopment in sound. One of the acoustical properties which result is reverberation, characterized classically by reverberation time, i.e., the time for a sound impulse to die away. But the period of growth of reverberant sound is not instantaneous. It results from an accumulating series of reflections from many surfaces which require time to develop. This gradual development of the reverberant sound in a typical auditorium occurs over a period of about 0.2 second.

The same principles may be employed to synthesize and convincingly simulate the sound of a good auditorium of controllable apparent size, all occurring in a small room, such as the living room of a home, the review room of a recording or broadcasting studio, or a large or small recording studio having highly absorptive acoustical surface characteristics. The technique consists in presenting to the listener, in addition to the direct sound from the source, a controlled series of simulated reflected sounds, plus an accumulating progression of reverberant sound. The present synthetic method produces this experience by starting with the same sounds and providing the series electro-acoustically. The method of synthesis should preferably use only sounds which are generated by natural acoustical means, but is not specifically so limited. For example, it is preferable that the reverberant sound should be generated in an acoustical space or reverberation chamber, although it may, with attendant loss of quality, be generated artificially by one of many known kinds of "reverberators." The gradual development of reverberant sound is simulated by the present method of synthesis, in contrast with earlier methods of artificial reverberation. Similarly, the delayed sound may be produced by means of an acoustical delay tube or by magnetic or other tape recording and playback means. Electro-acoustic means are used in the synthesis to the extent that the sound which in the actual auditorium is reflected from specific side wall or ceiling surfaces, is reproduced by loudspeakers which are properly positioned around the observers. The present invention assures that early simulated reflected sound will arrive at the listener from the proper directions at the proper controllable time intervals, and in the proper controllable intensity in relation to the direct sound.

The technique for synthetic auditorium sound may be applied either to real sounds generated directly in the audition room, as in the case of a piano, other instrument, or singer performing in the room, or it may be applied to sounds which have been recorded and are reproduced by usual means in the room. Under certain circumstances it may be applied to a multiplicity of sound sources, performers, or ensemble performing in the listening room.

There are essential differences between the method of synthesis contemplated by the present invention as compared with earlier methods. The differences are most convincingly demonstrated by comparative listening experience, but may be described and appreciated by the differences in the physical methods employed. It is important to realize that the success of any objective depends upon the degree of simulation achieved. Methods which are generally described by the term, "artificial reverberation," "artificial auditorium," etc. may produce a pleasing "effect" and a simulation which may bear com-

parison with certain limited types of sounds, such as slow moving organ or symphonic music. A more successful simulation will stand the test of comparison (real versus artificial) for a greater range of sound source material, as with the extreme of percussion sounds, or isolated sounds of clapping, or the pulse testing used in a real auditorium. The method of simulation used in the present invention stands the most severe test of comparison, produces a very convincing simulation to a degree that many very subtle properties of real concert halls occur in demonstration, and is therefore called "synthesis," because the simulation is produced by causing to occur the same series of acoustic events as in a particular chosen auditorium, or particular location within that auditorium. The distinctions between the artificial techniques and the synthesis technique may be clarified by brief reference to the prior art.

One system has proposed the use typically of a tape loop with multiple delay heads and with provision for reentrant signal from the last delay pickup back to the record head through an attenuator, which permits control of apparent reverberation time. The important distinction is in the nature of the simulated reverberation. In the re-entrant tape system the time delays between the individual "echoes" is usually made so long that they are easily perceived as separate echoes—a characteristic of bad auditoriums. Also, the transition from echoes to reverberation cannot occur in a natural way, because the rate of development of echoes is too slow, being limited by the number of pickups and re-entrant cycles which cannot approach the rapid development of multiple reflections of sound within a three-dimensional enclosure. The illusion produced by the re-entrant tape system is a useful "effect" and furnishes a useful simulation for slow moving sounds. However, for rapid music, speech or percussive sounds, the system results in the "flutter effect" which is a characteristic fault of a too simple acoustical space in which sound reflects one-dimensionally. Another effect called "coloration" tends to develop in re-entrant systems when the echo rate or the cyclic rate is increased, because either the "reverberation" time changes with frequency or the cyclic rate is apparent as a tone or a rhythm.

Another system uses the tape loop in combination with a reverberation chamber. The re-entrant feature is cited for use with the tape loop. However, the reverberation chamber is excited from only a single playback head. The problem is that one of two faults results: either the reverberation will be excited abruptly, by a single signal source, so that the transition from echoes to reverberation is instant, or, if the re-entrant feature is used, the chamber will be excited at uniform cyclic intervals, unlike the growth of real reverberation along with and as a result of multiple random reflections from several surfaces. In contrast, the present invention excites the chamber gradually with successive delayed signals derived from time intervals like those occurring in a real hall.

This invention departs most significantly from prior practices in its manner of producing reverberations and relating them to direct and synthesized reflected sounds, as characterized in the foregoing Abstract of the Invention.

The present method and means of synthesis may be more intimately understood by considering the acoustical phenomena of a concert hall by means of diagrams, and then relating the natural phenomena to the synthesis of these phenomena, in reference to the accompanying drawing.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is an acoustical diagram of a qualified auditorium or concert hall; and

FIG. 2 diagrams a typical system for synthetic acoustical simulation of a preconceived auditorium or hall as in FIG. 1.

DESCRIPTION OF THE ILLUSTRATIVE EMBODIMENTS

Sound originating at e.g. a stage source S in FIG. 1 proceeds directly toward the observer, O, along the path, d . The sound also reaches the observer by many reflected paths such as $r_1 \dots r_7$, which are typical of a few. Other reflections from single surfaces of the ceiling also reach the observer, as well as a succession of reflections from two surfaces, such as r_5 and r_6 . These reflections come from many directions. Since the sound paths are of different length, the time delays relative to the direct sound also vary. In general, the awareness of direction for two ear listening is good for sources displaced laterally about an observer, but less effective for sources elevated above the observer. Hence, it seems probable that angular position horizontally contributes most to the feeling of envelopment.

In a typical auditorium these principal single or double surface reflections will all have arrived to the listener in a time of about 0.2 second. Thereafter, multiple reflections arrive so frequently as to be essentially diffuse. Experiments demonstrate that reflections arriving within a time interval of 0.03 to 0.04 second are not perceived individually, i.e., if several reflections or "mini-echoes" arrive in a group encompassing a time interval of 0.03 second, i.e., 30 milli-seconds, they will be perceived as a single echo. Similarly, if there are no time gaps greater than about 40 milli-seconds, they are not perceived as gaps, nor are the following echo-groups detected as echoes. These principles, which must be observed in the design of a real auditorium, also guide the process of synthesis.

In FIG. 2, the sound source S within the listening room R sends sound directly to the observer, O. The source may be either a real sound or sound reproduced from recording and projected from a loudspeaker. No reflected sound having proper delay to give an impression of large space is perceived by the observer, because either (a) the enclosing boundaries are highly absorptive, as in a good multi-use studio, or (b) the enclosure is so small that reflected sounds arrive very quickly and die away very quickly, as in the typical living room.

The simulation of delayed reflected sound is achieved by use of a delay tube T which is generally of sufficient length to prolong the sound throughout the range of desired incremental delay. Ordinarily the length of the tube T will exceed the maximum dimension of the room R. The delay tube is driven by a loudspeaker L_T , receiving electrical energy through an amplifier W and gain control G from either a microphone in front of the real sound source, or from the electrical signal driving the source loudspeaker. At any point a distance d along the delay tube the signal is delayed by a time interval

$$\Delta t = \frac{d}{c}$$

where c is the velocity of the sound wave in the tube, which is somewhat less than the sound velocity in free space. Thus, the time delay in milli-seconds will be slightly less than the distance in feet. The sound at various delay intervals may be detected and corresponding electrical signals derived by a series of microphones $M_1, M_2 \dots M_n$ (n being an indefinite number) inserted into the wall of the tube. Each microphone signal is amplified and carefully equalized to accommodate for the attenuation along the tube, and is fed to a specific loudspeaker among those arranged at $L_1 \dots L_5$ in the room walls about the listener location O.

In a real auditorium seating perhaps 2500 people, the early reflections may arrive at a typical audience position after time intervals varying randomly from 25 to 100 milli-seconds. These intervals depend of course to some

extent on seating position and on the size and shape of the hall. Correspondingly, the time intervals desired for delay from the delay tube may be randomly spaced. If t is the time delay in the tube, the delay experienced by the observer is

$$\Delta T = \frac{L \text{ to } O}{c} + \Delta t - \frac{S \text{ to } O}{c}$$

where L to O is the distance from the room speaker to O . Without the delay tube, it is possible that the sound from a typical loudspeaker L_1 may arrive earlier than the direct sound. In general, however, the distances S to O and a room speaker to O will be comparable and small compared to the desired time delay T . One interesting corollary is that many observers in a small listening room will experience about the same series of delays and auditorium simulation, since, if the delay tube distances L_T to the tube microphones are long compared to the listening room dimensions, the delay times rather than the distances to loudspeakers or source will control.

Though less effectively, the series of delayed signals may also be derived by the use of tape recording and playback using a series of playback heads past which the tape moves in succession. An essential feature of the method of synthesis here presented is that the series of delayed simulated reflections projected from the loudspeakers $L_1, L_2 \dots L_n$ (n being an indefinite number) occur or are presented to the observer at time delay intervals comparable with the delays experienced in a concert hall or auditorium as may be determined by proper correlations with FIG. 1. Also, the relative intensities of the reflections, and individual intensities, may be separately controlled by attenuators of the G_D group in the electrical paths from microphones to loudspeakers, so as to simulate the relative strengths of real echoes from the surfaces of a specific auditorium. Likewise, equalizers may be inserted in each line to simulate the frequency response characteristic of reflections from reflectors of various sizes.

Another characteristic of real reflections in a hall is that, for most seat positions, or in the most desirable seat locations, the progression of reflections arrives at later times as the angle of arrival increases from front to rear. In FIG. 1, for example, r_3 arrives later than r_1 , and r_6 later than r_4 . At a particular seat toward the rear of a hall, r_7 may arrive earlier than r_6 , for example. In the simulation method, the order of arrival of simulated reflections from $L_1 \dots L_n$ may be controlled merely by selecting which typical delay microphone M shall feed each room loudspeaker L . Thus a feature of the method is that the listeners in the simulated hall may be "placed" in various simulated positions in the apparent hall, or all may in effect be placed in an optimal or favored position. The number of loudspeakers $L_1 \dots L_n$ which is used, or the number of microphones or delay positions along the delay tube, is determined by the degree of perfection of simulation desired. It will also be determined by the acuity of perception which the typical individual can achieve. For example, an actual hall may be designed so that each seating position receives reflections from at least three wall panels on each side. Inasmuch as evidence indicates that multiple echoes which occur from a given direction within about 30 to 40 milli-seconds are perceived as one, it may be that a fewer number of simulated reflections will suffice. Experience alone can give the most economic, or practical, or adequately convincing numbers.

Another feature of the real auditorium sound is that diffuse sound, i.e., the very closely spaced small reflections which constitute the reverberant sound, develops in intensity only gradually. Usual methods of artificial reverberation introduce reverberant sound practically instantly. This corresponds to the reverberant sound production in a small room and hence cannot convincingly simulate a large room. In a large real concert hall there are two

methods by which diffuse sound develops. Along the path to the observer any sound impulse is scattered by nearby small obstacles such as music stands, chairs, architectural embellishments, lighting fixtures, adjacent people, etc. This is "instant" diffusion, like a fringe on the mini-echo. After a time interval, the principle echoes or reflections have struck many surfaces and are arriving very frequently and from a multitude of directions at each observer position. The significant thing is that the reverberant sound develops gradually during and after the time that the important envelopmental reflections are occurring.

These phenomena are simulated in the synthesis method as follows: The delayed signal from each microphone $M_1 \dots M_n$ is fed separately into a reverberation chamber C in sequence through a mixing network, an amplifier, and a loudspeaker L_c . The amount of signal from each delay microphone is controlled by a separate gain control $G_1 \dots G_5$, and these are adjusted to assure a gradual and smooth buildup of sound excitation to the chamber. This is an important feature for greatest success of the synthesis technique. In general, the proportion of energy fed to the chamber will increase with the time delay of the particular delay microphone.

Chamber C preferably is an enclosure of unequal side and end wall lengths, and in a typical instance may be a rectangular configuration in the order of sound 11 feet width and 14 feet length, with the chamber height about 9 feet. The reverberant sound developing in the chamber is detected by one or preferably more microphones, shown as M_{c1} and M_{c2} and the resulting electrical signals are fed by mixing into any or several of the loudspeakers $L_1 \dots L_n$ in the listening space. Thus the reverberant sound, being delayed for insertion into the reverberation chamber by the delay tube, builds slowly in intensity, as returned to the listening space by the surrounding loudspeakers. Since the dimensions of the reverberation chamber will in general be considerably smaller than for the listening space, or the real hall, the time delay for the build-up of reverberation is controlled largely by the delays along the delay tube, which are comparable with delays in a real hall.

Loudspeaker L_c exciting the chamber is shown in a corner, because acoustical theory as well as experience prove that a small chamber will furnish that best sound if excited at a corner. Similarly, the pick-up microphones M_{c1} and M_{c2} are shown and best mounted in opposite corners for the same reason.

The decay rate of reverberant sound in a hall is determined by its volume and absorption. A typical or desirable reverberation time will be the order of 2 seconds. The desirable value of reverberation time will depend upon the type of performance, being longer for music and shorter for plays, to preserve speech intelligibility. In the synthesis technique the reverberation time will be controllable by adjustment of the amount of acoustic absorption in the reverberation chamber. Also, an important parameter of an auditorium, and hence of the synthesis technique, the reverberation time may be made different for various frequencies. For example, for music it is desirable that the reverberation be more extended at lower frequencies than at higher frequencies, whereas for speech in a theater relatively less low frequency reverberation is preferred. These effects may be achieved in the synthesis by adjusting the relative amounts and types of absorptive material placed in the reverberation chamber.

In an actual hall, as previously observed, the sound perceived by a listener may be described as of three types: the direct sound, the envelopment sound from early reflections, and the reverberant sound. The relative intensities of each of these component types of sound may be controlled to a degree in a real hall by careful acoustical design. The perceived effect is similarly variable. If the direct sound dominates, clarity and intelligibility are apparent. If reverberant sound intensity dominates, a feel-

ing of distance and confusion develops. In the synthesis method, the relative degrees or intensities of these three types of sound can be separately and easily controlled by simple electrical attenuators G_D and G_R .

Results achieved with the present system of synthesis, derived from real concert hall parameters, demonstrates that it displays many characteristics of real halls. For example: it handles convincingly the full gamut of real speech and musical sounds, including percussion music, and even the test pulses we use to measure a real auditorium; the envelopment effect varies as in a hall the character of the music, spreading for large ensemble passages, and focusing for solo passages; the apparent amount of bass sound increases when the repetition rate of sounds is comparable with the delay intervals; when adjusted for music, speech intelligibility can be enhanced by increasing direct sound only, as is done with effective sound reinforcement in a good auditorium; even the severe aberrations of poorly designed halls can be synthesized, such as discrete echoes, lack of side wall reflection or envelopment, delayed reverberation, poor intelligibility, etc. Thus, this method of synthesis represents an advance in the art which will permit greater utility and versatility of specialized spaces for real sounds, such as television studios, as well as more enjoyable listening for reproduced sound in small rooms.

I claim:

1. The method of synthesizing sounds for simulation of sounds produced in an acoustically predetermined auditorium in which sound created at a stage location is transmitted from said location directly to an audience location and indirectly thereto by side wall sound reflections in said auditorium and by reverberation; said method including the steps of producing program sound at a first location in a relatively small listening room and transmitting the sound within the room atmosphere directly to a listener location therein, subjecting energy productive of the program direct sound as it is produced to progressively extended delay beyond the time of the direct sound transmission from said first location to the listener location, selecting and transmitting into the room atmosphere increments of the delayed energy as delayed sounds and in predetermined relation to said auditorium side wall reflected sounds, subjecting sequential increments of the delayed energy to reverberation, and transmitting the accumulated reverberated energy as sound into the room atmosphere.

2. The method of claim 1, in which said delayed energy is subjected to reverberation as sound within an enclosed reverberation space.

3. The method of claim 1, in which said delayed sound increments are transmitted into the room atmosphere from side wall locations distributed about said listener location.

4. The method of claim 3, in which the reverberated sound is transmitted to the room atmosphere at said side wall locations together with at the same locations as said delayed sound increments.

5. The method of claim 4, in which the listening room walls are sound absorptive.

6. The method of claim 1, in which sequential increments of the delayed energy are relatively varied in magnitude in advance of reverberation.

7. The method of claim 6, in which said sequential increments are individually varied in magnitude.

8. The method of claim 1, in which said auditorium is preconceived to have predetermined time values for (1) direct sound transmission from said stage location to a selected audience location, (2) indirect transmissions of sounds by reflections from auditorium side walls to the audience location, and (3) generation and transmission of reverberated sound thereto, and in which time differentials in transmission of direct and side wall reflected listening room sounds to the listener location are substantially in accordance with the differentials of said values (1) and (2).

9. The method of claim 8, in which the time differentials in generation and transmission of reverberated sound to said audience location are substantially in accordance with the differential of said values (1) and (3).

10. The method of claim 1, in which said energy productive of the program sound is subjected to progressively extended delay by projection as sound through a passage formed by an extended tube, and said increments are derived from spaced locations along said passage.

11. The method of claim 10, in which the length of said passage between the locus of sound projection therein and at least one of said locations is greater than the maximum listening room dimension.

12. The method of claim 10, in which at least certain of said passage derived increments are fed as sound into an enlarged reverberation chamber to produce the reverberated sound for transmission to the listening room.

13. The method of claim 12, in which said passage derived increments are relatively varied in magnitude in advance of reverberation.

14. In combination with a listening room containing a program sound source and a listener location spaced therefrom so that program sound is transmitted directly from said source within the room atmosphere to the listener location,

(A) means receiving and subjecting said energy productive of the program sound as it is produced to progressively extended delay beyond the time of the direct sound transmission from said source to the listener location,

(B) means for selecting and transmitting into the room atmosphere increments of the delayed energy as delayed sounds,

(C) and means for subjecting sequential increments of the delayed energy to reverberation and for transmitting the accumulated reverberated energy as sound into the room atmosphere.

15. The combination of claim 14, in which said means (A) comprises an extended delay tube outside the room and into one end of which said program productive energy is projected as sound, and said means (B) comprises microphones positioned at spaced locations along the sound passage within the tube and connected to speakers positioned to transmit delayed sound increments into the room from side wall locations distributed about the listener location.

16. The combination of claim 15, in which the length of said delay tube is greater than the maximum dimension of the listening room.

17. The combination of claim 14, in which said means (C) comprises an enlarged chamber outside the listening room and into which said delayed energy increments are transmitted as sounds to be reverberated by mixed reflections from the chamber walls.

18. The combination of claim 15, in which said means (C) comprises an enlarged chamber outside the listening room into which said delayed energy increments are transmitted by said microphones as sounds for reverberation, and means transmitting reverberated sound from said chamber to said listening room speakers.

19. The combination of claim 18, including means operable to vary the magnitude of energy transmitted from said microphones to the reverberation chamber.

20. The method of synthesizing sounds for simulation of sounds produced in an acoustically predetermined auditorium in which sound created at a stage location is transmitted from said location directly to an audience location and indirectly thereto by side wall sound reflections in said auditorium and by reverberation, said method including the steps:

(a) producing program sound at a first location in a relatively small listening room and transmitting the sound within the room atmosphere directly to a listener location therein,

- (b) detecting such program sound production and producing a version thereof,
- (c) obtaining differently time delayed samples of said version of the program sound production,
- (d) transmitting into the room atmosphere sound energy directly corresponding to said samples, 5
- (e) reverberating sound energy corresponding to said samples to produce a reverberated version thereof,
- (f) and transmitting into the room atmosphere sound energy corresponding to said reverberated version 10 of the samples.

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