(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
24 March 2016 (24.03.2016)

WIPO | PCT

(10) International Publication Number
WO 2016/042410 A1

(51) International Patent Classification:
H04S 7/00 (2006.01) *H04R 7/04* (2006.01)

(21) International Application Number:
PCT/IB2015/002019

(22) International Filing Date:
17 September 2015 (17.09.2015)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
62/051,519 17 September 2014 (17.09.2014) US

(71) Applicant: **SYMPHONOVA, LTD** [GB/GB]; 71-75 Shelton Street, Covent Garden, London WC2H 9JQ (GB).

(72) Inventor: **KATZ, Shelley**; Whitegables, 24 Holmesdale Road, Bexhill on Sea, East Sussex TN39 3QE (GB).

(74) Agent: **THIBON, Laurent**; Cabinet Beaumont, 1, Rue Champollion, F-38000 Grenoble (FR).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*

— *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments (Rule 48.2(h))*

WO 2016/042410 A1

(54) Title: TECHNIQUES FOR ACOUSTIC REVERBERANCE CONTROL AND RELATED SYSTEMS AND METHODS

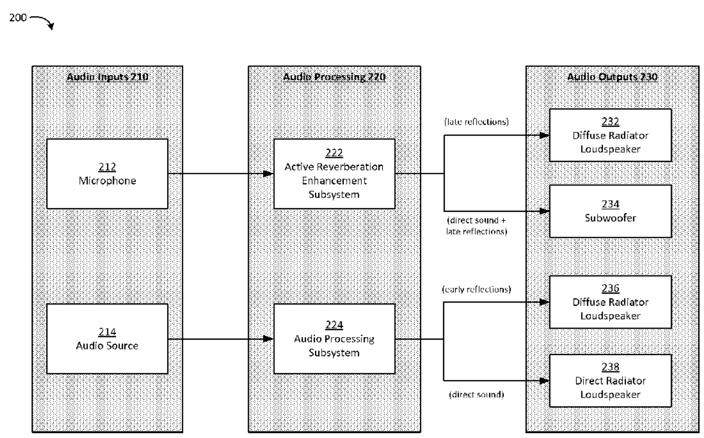


FIG. 2

(57) Abstract: According to some aspects, an audio system is provided, comprising at least one microphone configured to capture ambient sound within a listening space, a diffuse radiator loudspeaker configured to produce incoherent sound waves, and a reverberation processing unit configured to apply reverberation to at least a portion of ambient sound captured by the at least one microphone, thereby producing modified sound, and output the modified sound into the listening space via the diffuse radiator loudspeaker. According to some aspects, a method is provided comprising capturing ambient sound within a listening space using at least one microphone, applying reverberation to at least a portion of the ambient sound captured by the at least one microphone, thereby producing modified sound, and outputting the modified sound into the listening space from an incoherent diffuse radiator loudspeaker.

TECHNIQUES FOR ACOUSTIC REVERBERANCE CONTROL AND RELATED SYSTEMS AND METHODS

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] The present application claims the benefit under 35 U.S.C. §119(e) of U.S. Provisional Patent Application No. 62/051,519, filed September 17, 2014, titled "Acoustic System and Method for Acoustic Reverberance Control of Sound in a Listening Space," the entire content of which is hereby incorporated by reference.

BACKGROUND

[0002] Sounds produced by loudspeakers generally interact in a complex manner with the environment. Typically, a listening space will comprise numerous surfaces that each reflect sound waves to varying extents. In some cases, acoustic reflectiveness of a surface may depend upon the frequency of the sound incident on the surface. The sum total of such interactions in a typical listening space, such as a concert hall or living room, produces an extremely diverse array of sound waves being scattered around the space, even when generated from a single audio source.

[0003] Moreover, when these sound waves reach the ears of a listener, further complex effects may occur. Due to the spatial separation between human ears, the effect of sound waves heard by a listener may be quite different when sound reaches both ears at the same time compared with cases in which there is a difference in arrival time of the sound at each ear. Moreover, sound waves incident on the ear may destructively and/or constructively interfere due to the nature of the sound source as well as various path lengths that the sound may have travelled from the audio source to the ear, which can further affect how sound is heard.

SUMMARY

[0004] The present application relates generally to techniques of acoustic reverberance control.

[0005] According to some aspects, an audio system is provided comprising at least one microphone configured to capture ambient sound within a listening space, a diffuse radiator loudspeaker configured to produce incoherent sound waves, and a reverberation processing unit configured to apply reverberation to at least a portion of ambient sound captured by the at least one microphone, thereby producing modified sound, and output the modified sound into the listening space via the diffuse radiator loudspeaker.

[0006] According to some aspects, a method is provided comprising capturing ambient sound within a listening space using at least one microphone, applying reverberation to at least a portion of the ambient sound captured by the at least one microphone, thereby producing modified sound, and outputting the modified sound into the listening space from an incoherent diffuse radiator loudspeaker.

[0007] The foregoing is a non-limiting summary of the invention, which is defined by the attached claims.

BRIEF DESCRIPTION OF DRAWINGS

[0008] Various aspects and embodiments will be described with reference to the following figures. It should be appreciated that the figures are not necessarily drawn to scale. In the drawings, each identical or nearly identical component that is illustrated in various figures is represented by a like numeral. For purposes of clarity, not every component may be labeled in every drawing.

[0009] FIG. 1 is a block diagram of an illustrative audio system, according to some embodiments;

[0010] FIG. 2 is a block diagram of an illustrative audio system that receives input from an audio source and one or more microphones, according to some embodiments;

[0011] FIG. 3 is a block diagram of an illustrative active reverb enhancement subsystem, according to some embodiments;

[0012] FIG. 4 is a block diagram of an illustrative audio processing subsystem, according to some embodiments;

[0013] FIGs. 5A-5C depict an illustrative apparatus for housing an audio system, according to some embodiments; and

[0014] FIG. 6 illustrates an example of a computing system environment on which aspects of the invention may be implemented.

DETAILED DESCRIPTION

[0015] As discussed above, sounds produced by a loudspeaker generally produce a complex array of sounds whose amplitudes and times of arrival at a listener's ear depend highly on spatial dimensions and reflective properties of the listening environment. The same sound source placed, for example, within a concert hall will sound extremely different to a listener than the same sound source placed in a living room. Moreover, the sound heard by the listener will often change drastically as the listener moves around within the listening environment. While a number of techniques exist to assess the extent to which these effects occur in practice, one important measure is that of "reverberation" (sometimes simply called "reverb"), which is an indication of how much sound persists after it is produced. One commonly used reverberation metric is RT60, which is the time taken for a sound to drop in amplitude by 60dB. Metrics such as RT60 are simply indications of the complex interactions described above, however, and are simply used as convenient yet imprecise measurements of a listening environment's response to sound.

[0016] Since a listener's experience can be so drastically different for the same audio source in different environments, a number of existing systems attempt to artificially produce reverberation effects in otherwise low reverberation (also sometimes referred to as "dry") listening environments. For instance, surround sound systems featuring multiple speakers are often used in home theaters. However, such systems generally simply output an audio signal that is sent to each loudspeaker and do not differentiate between different reverberant environments being depicted in the movie or television show. Moreover, arrangements of directional loudspeakers such as those found in surround sound systems or in more complex systems often require careful placement of the speakers to produce the desired listening experience.

[0017] Even when an audio system produces sounds having reverb that fits an acoustic environment being presented, unless the reverb matches a listener's space it can readily become apparent to the listener that they are not actually in such a space. For instance, as soon as a listener speaks, moves or creates any noise in the listening environment, there can be an apparent disconnect between the acoustics of the audio and the acoustics of the real-world environment. The listener may thereby perceive the disconnect, which may disturb the suspension of disbelief that those in the listening environment have created for themselves. For example, an audio system producing sounds of a musical concert with reverb that would typically be experienced in a large concert hall may be believable by a listener in a living room to some degree, but as soon as the listener speaks or moves, the illusion of being in a large concert hall may be destroyed.

[0018] In view of the above, the inventor has recognized and appreciated that control over a listening environment in terms of the reverberance of sound produced by an audio system and/or sound produced within the environment may provide an enhanced listening experience. By providing an audio system with such control over the listening environment, real-world acoustics of the listening environment and acoustics presented by the audio system may be matched, so that the real and the virtual acoustic spaces may be seamlessly blended together. The audio system described herein may therefore include at least one of two primary aspects: a first aspect to control reverberance of real acoustics of a listening environment, and a second aspect to control reverberance of virtual acoustics of an audio source (e.g., a music recording).

[0019] With respect to the first of these aspects, the inventor has recognized and appreciated that capturing ambient sound from a listening environment and rebroadcasting the ambient sound with added reverb through appropriate sound radiators can cause a listener to become immersed in a presented acoustic environment by effectively altering the reverberance of the listening environment. Sounds originating from within the environment may be captured by a microphone, and audio may thereafter be produced from a suitable loudspeaker within the environment to supplement the sounds and to give the effect of those sounds reverberating through the environment differently than they would naturally.

[0020] The inventor has further recognized and appreciated that by producing such audio from a diffuse radiator loudspeaker, the audio system may produce dispersed sound having similar qualities to a system of multiple directional loudspeakers, yet without the need for complex positioning and without the same susceptibility to destructive interference and/or feedback. Furthermore, the inventor has recognized that an incoherent diffuse radiator loudspeaker may be particularly beneficial in mimicking naturally produced reverberating sound (that is, sound produced purely from reflections within a listening space). While natural reverberant sound has a characteristic sound content, it also has physical characteristics due to the way in which the reverberance is produced by the environment which include a lack of coherence in the component sound waves. Accordingly, an incoherent loudspeaker (e.g., one having an interaural cross-correlation (IACC) coefficient below 0.7, or below 0.5, such as around 0.3) may be particularly effective at producing reverberant sound that appears similar to, or substantially identical to, naturally reverberant sound.

[0021] Accordingly, by combining a microphone positioned in a listening environment, with a system able to generate audio that creates a desired reverberant effect in the environment, and with an incoherent diffuse radiator loudspeaker that outputs such audio, reverberance of the real acoustics of the listening environment may be controlled.

[0022] Application of reverberation to sound generally includes multiple aspects such as application of a time delay and adjustment of sound properties. However, since a time delay may naturally occur due to the processing time that transpires between capturing ambient sound, applying reverberation and outputting the resulting sound (e.g., due to a physical distance between the microphone and the loudspeaker, due to processing time, etc.), application of reverberation need not necessarily comprise applying a time delay (or at least may not include as much time delay as might be conventionally applied). Other aspects of reverberation typically applied in other cases may still yet be applied to captured sound.

[0023] According to some embodiments, the use of diffuse radiator loudspeakers in the audio system described herein may provide numerous advantages over systems that use conventional direct radiator loudspeakers. Radiation may be produced from a diffuse radiator loudspeaker at multiple points on a panel, thereby producing dispersed, and in some cases, incoherent sound radiation. Accordingly, one panel loudspeaker may effectively provide multiple point sources that are decorrelated with each other. In contrast, conventional systems may use multiple piston loudspeakers that produce coherent sound and whose number and location relative to a microphone have to be considered to reduce feedback between components. Conventional systems may also rely on signal processing to produce a stable gain.

[0024] Another advantage of diffuse radiator loudspeakers is that they are generally not proximity sensitive. Sound systems including direct radiator loudspeakers are typically designed such that there is an optimal listener position, so that a listener at a non-optimal position may experience louder listening conditions as the listener moves closer toward the direct radiator loudspeaker. In contrast, because of the sound distribution characteristics of a diffuse radiator loudspeaker, a listener may be positioned near the loudspeaker without the sound appearing to be too loud. Thus, multiple listeners at different listener positions may still experience comfortable listening conditions with a diffuse radiator loudspeaker.

[0025] With respect to the second of the aspects noted above, namely the control of reverberance of the virtual acoustics of an audio source, the inventor has recognized and appreciated that an audio source may be included within the audio system described herein and its reverb reproduced to match the reverb of a listening environment. This may include first removing any reverb already present in an audio source (e.g., music recording, movie soundtrack, etc.) and then adding reverb to produce a desired effect. In some embodiments, a desired effect may depend upon acoustic properties of a listening environment in which the audio system is located. In some cases, the reverberation of the ambient environment reproduced as described above may be performed to match reverb present within the audio source.

[0026] According to some embodiments, an audio system as described herein may identify different components of an audio signal having different reverberance, and may output at least one of those components to a particular loudspeaker based on those properties. The loudspeaker may be selected, for example, due to its compatibility with properties of the identified component(s). Such components may be identified based on the time from commencement of direct sound in the audio signal. As one non-limiting example, an audio system may identify one or more of: direct sound (e.g., sound originating between 0 - 5 ms from initiation of sound), early reflections (e.g., sound originating between 5 ms - 80 ms from initiation of sound), and late reflections (e.g., sound originating more than 80 ms from initiation of sound). Each identified reverberance component may be output by a speaker and/or speaker type (e.g., diffuse radiator or direct radiator) preselected based on the type of component. For instance, in some embodiments direct sound may be separated out of an audio signal and output by a direct radiator loudspeaker, whereas early reflections may be separated out of the audio signal and output by a diffuse radiator loudspeaker. In some embodiments, control over the reverberant components of an audio signal may be performed by removing or otherwise reducing the effect of an identified reverb component of the audio signal, and/or by adding additional reverb to one or more identified reverb components.

[0027] Following below are more detailed descriptions of various concepts related to, and embodiments of, systems and methods for acoustic reverberance control. It should be appreciated that various aspects described herein may be implemented in any of numerous ways. Examples of specific implementations are provided herein for illustrative purposes only. In addition, the various aspects described in the embodiments below may be used alone or in any combination, and are not limited to the combinations explicitly described herein.

[0028] FIG. 1 is a block diagram of an illustrative audio system, according to some embodiments. System 100 includes one or more audio inputs 110, one or more audio processing components 120 and one or more audio outputs 130. In the example of FIG. 1, the audio inputs include a microphone 112, the audio processing components include an active reverberation enhancement subsystem 122, and the audio outputs include a diffuse radiator loudspeaker 132.

[0029] As discussed above, capturing sound from a listening environment using a microphone, then rebroadcasting the sound with added reverb using suitable sound radiators, can cause a listener to become immersed in a presented acoustic environment by effectively altering the reverberance of the listening environment. FIG. 1 presents an illustrative audio system configured to perform such an operation. Further systems that can also control reverberance of the virtual acoustics of an audio source will be discussed below.

[0030] System 100 may be used, for instance, to balance the frequency response of an environment in which the system is located. In such a case, the microphone 112 may capture ambient sound from the environment and provide an electrical signal indicative of the sound to active reverberation enhancement subsystem 122. The active reverberation enhancement subsystem 122 may apply reverberation to some or all of the captured ambient sound, and output the resulting sound via diffuse radiator loudspeaker 132.

[0031] Since the sound may be output while ambient sounds are propagating through the environment, the resulting effect to a listener in the environment may be that the reverberance of the environment has been altered by the system. As one non-limiting example, system 100, when placed in a living room, may capture ambient sounds (e.g., people moving, talking, etc.), apply reverb to some or all of the captured sound and output the sound with reverb though the diffuse radiator loudspeaker. Those ambient sounds may thereby be propagated in a different manner through the environment than they would otherwise be in the absence of system 100. The net effect to a listener may be, for example, that when they speak they hear their voice as if they were in a much larger room.

[0032] As another non-limiting example, system 100 may be used within a conference room to increase the clarity of sounds within the room by ensuring that the reinforced frequencies of early reflections do not drop below about 5 kHz. This may, for example, be performed by adjusting the output frequencies from active reverberation enhancement subsystem 122 via equalization hardware and/or software whilst also adding reverberance to the sound. For instance, the equalization hardware and/or software may increase levels of sound above 5 kHz (and may optionally reduce levels of sound below 5 kHz). In large acoustic spaces, consonants of speech tend to have lower sound pressure levels (SPLs) above around 3-5 kHz. Reinforcing sounds above around 3-5 kHz can help a listener to understand speech in such a space because softer parts of speech, which are often the most useful, may be easier to comprehend as a result.

[0033] Microphone 112 may include any suitable microphone able to capture ambient sounds within its environment. Microphone 112 may preferably be an omnidirectional microphone, though may also be a unidirectional or bidirectional microphone in some embodiments. According to some embodiments, the microphone may be a dynamic or a condenser microphone. Microphone 112 may have any suitable frequency response and dynamic range, such as a substantially flat frequency response between about 30 Hz and about 10 kHz, or between about 20 Hz and about 20 kHz, such as between 100 Hz and 5 kHz. Microphone 112 may be a wireless or a wired microphone.

[0034] According to some embodiments, active reverberation enhancement subsystem 122 may include one or more dedicated hardware components configured to apply reverberation to incoming sound signals. For instance, active reverberation enhancement subsystem 122 may include one or more effects processors, such as a rack-mountable FX unit. An illustrative active reverberation enhancement subsystem is described in further detail below in relation to FIG. 3.

[0035] According to some embodiments, active reverberation enhancement subsystem 122 may include one or more software components. Accordingly, in some embodiments, active reverberation enhancement subsystem 122 may include, and/or may be coupled to, a suitable computer system such as computer system 600 shown in FIG. 6 and discussed below. In some embodiments, such a computer system may include software for rendering and/or processing audio signals, such as AudioDesk produced by MOTU, and/or may include software for applying reverberation, such as Vienna MIR PRO.

[0036] Diffuse radiator loudspeaker 132 may include any suitable loudspeaker that operates on the basis of a vibrating, resonating panel and that therefore propagates an incoherent air-disturbance pattern or sound wave-form. In such a loudspeaker, sounds are the result of transverse waves that are induced in the panel, and not the result of, for example, the pistonic motion of a diaphragm. According to some embodiments, motion of the panel may be produced by a driver such as an electromagnetic voice-coil or other electroacoustic exciter coupled to the surface of the panel. In some embodiments, the frequency response of the panel may be optimized by adding weights and/or other modifiers to the surface of the panel, and/or adjusting the restraint of the panel's edge at selected points.

[0037] According to some embodiments, diffuse radiator loudspeaker 132 may exhibit an anechoic inter-aural cross-correlation (IACC) coefficient that is less than about 0.7, and in some cases may be less than about 0.5. According to some embodiments, diffuse radiator loudspeaker 132 may exhibit an IACC coefficient between 0.1 and 0.7, such as between 0.2 and 0.5, such as 0.4. Diffuse radiator loudspeaker 132 may include, but is not limited to, any loudspeaker type referred to as a distributed mode loudspeaker, a transverse wave panel loudspeaker, a bending wave panel loudspeaker or a multi-actuator panel (MAP) loudspeaker.

[0038] FIG. 2 is a block diagram of an illustrative audio system that receives input from an audio source and one or more microphones, according to some embodiments. System 200 may provide the functionality discussed above in relation to system 100 via elements 212, 222 and 232 (for which the above discussions of elements 112, 122 and 132, respectively, are referenced), and in addition may provide for control of reverberance of the virtual acoustics of an audio source 214 via audio processing subsystem 224 and loudspeakers 236 and 238. In addition, a subwoofer 234 is included as another loudspeaker to which active reverberation enhancement subsystem 222 outputs sound.

[0039] In the example of FIG. 2, active reverberation enhancement subsystem 222 produces two output signals: a first comprising late reflections that is output via diffuse radiator loudspeaker 232, and a second comprising both direct sound and early and/or late reflections that is output via subwoofer 234.

[0040] As discussed above, late reflections are generally those sounds that begin around 80 ms after direct sound output is initiated, and may be produced by active reverberation enhancement subsystem 222 by applying suitable reverb effects to the received sound input from microphone 212, such that the sound mimics late reflections of the direct sound. The sound produced with late reflections may be output to both the subwoofer 234 and diffuse radiator loudspeaker 232, and in addition the direct sound captured by the microphone may be output from subwoofer 234.

[0041] Audio source 214 may include any device or devices able to playback or otherwise output sound generated from a source, such as, but not limited to, a CD player, a DVD player, a Bluetooth device, an MP3 player, a television, a receiver, a computer, a tablet, a mobile device, a microphone, or combinations thereof.

[0042] Audio processing subsystem 224 performs separation of components of audio received from the audio source 214 based on the components' reverberance. That is, the received audio may be separated into components representing such aspects as direct sound, early reflections and/or late reflections, although other components having different reverberance may also be generated (e.g., for clarity, such as special effects). The audio processing subsystem may perform this operation using any suitable combination of hardware and/or software. As such, in some embodiments, audio processing subsystem 224 may include, and/or may be coupled to, a suitable computer system such as computer system 600 shown in FIG. 6 and discussed below.

[0043] Any suitable approach may be employed by audio processing subsystem 224 to generate components from an audio signal based on reverberance. In some embodiments, a process known as "dereverberation," which seeks to identify the direct sound from an audio signal, may be performed to separate out early and late reflections. In some embodiments, audio processing subsystem 224 may perform dereverberation to identify a direct sound component of an audio signal, and then use the direct sound to identify remaining components that persist in the audio signal other than the direct sound. Illustrative processing techniques that may be used by audio processing subsystem 224 include, but are not limited to, dereverberation via spectral subtraction, dereverberation using channel inversion and equalization, automatic speech recognition, voice activity detection, acoustic echo cancellation (AEC), residual echo estimation, adaptive filter, double-talk detection, non-linear processing, or combinations thereof.

[0044] According to some embodiments, audio processing subsystem 224 may perform digital signal processing on the received signal from audio source 214 before performing the above-described separation of components. Such processing may include, but is not limited to, equalization adjustments, loudness adjustment, frequency tuning, applying a compressor and/or expander, addition of delay or other effects, or combinations thereof.

[0045] Sound components generated by audio processing subsystem 224 based on their reverberance are output to loudspeakers 236 and 238. In the example of FIG. 2, particular components are sent to particular loudspeakers; specifically, an early reflections component of the audio signal received by audio processing subsystem 224 is output to diffuse radiator loudspeaker 236 and a direct sound component of the audio signal is output to direct radiator loudspeaker 238. Accordingly, in this example, a dry signal is output by direct radiator loudspeaker 238 and a reverberant signal is output by diffuse radiator loudspeaker 236.

[0046] Direct radiator loudspeaker 238 may be any loudspeaker. According to some embodiments, direct radiator loudspeaker 238 may include any loudspeaker that, regardless of its method of operation (e.g., cone, electrostatic, ribbon, etc.) has an anechoic IACC measurement above about 0.7 (e.g., indicating a beamed acoustic radiation and binaurally correlated air-disturbance pattern).

[0047] Since sound that is output by diffuse radiator loudspeaker 236 and/or direct radiator loudspeaker 238 will propagate through the listening environment in which system 200 is located, these resulting sounds will generally be captured by microphone 212. Microphone 212 may therefore, in at least some embodiments, capture a blend of ambient sounds produced from the environment and sound produced from any of loudspeakers 232, 234, 236 and/or 238. In this manner, the system 200 could be viewed as providing a "recursive" sound since output(s) of the system may be fed into one or more inputs, which may consequently change the output(s), which may be fed into one or more inputs, etc.

[0048] FIG. 3 is a block diagram of an illustrative active reverb enhancement subsystem, according to some embodiments. According to some embodiments, active reverb enhancement system 300 may be used as element 122 and/or element 222 shown in FIGs. 1 and 2, respectively. Active reverb enhancement system 300 receives input from one or more microphones or other audio sources, applies reverb to sound input via reverberation unit 310, and outputs sound to one or more loudspeakers via amplifier(s) 330. Active reverb enhancement system 300 optionally includes a digital signal processing (DSP) unit 320.

[0049] According to some embodiments, reverberation unit 310 may include one or more hardware components configured to apply reverberation to incoming sound signals. In some embodiments, reverberation unit 310 includes circuitry comprising a plurality of filters and multiplexors that produce an output signal representing audio having reverb based on an input audio signal. Such filters may include, but are not limited to, all-pass, comb, high pass, low pass, EQ filters, or combinations thereof. In some embodiments, reverberation unit 310 may produce an output signal representing audio having reverb compared with an input audio signal using software (in which case reverberation unit 310 may include and/or may be coupled to, a suitable computer system). In some embodiments, reverberation unit 310 may apply a reverb amount and/or type based on a reverberation preset of active reverb enhancement system 300 (e.g., selected via a user interface that may be produced via hardware and/or software).

[0050] According to some embodiments, reverberation unit 310 may apply reverberation to an input audio signal based on an audio source and/or based on a listening environment in which system 300 is located. Both of these techniques of applying reverberation are described as follows.

[0051] In some embodiments, whether and how much reverberation is applied by reverberation unit 310 may depend upon an audio source being input to a system in which active reverb enhancement system 300 is operating. For instance, in system 200 adding reverb using active reverberation enhancement subsystem 222 may not always make sense, depending on the content of audio source 214. As one example, if system 200 receives audio from a movie as audio source 214, and the acoustic scene in the movie is exceedingly “dry” and quiet (perhaps a conversation is taking place in a clothes closet) there will be scenic environmental noises, such as the rustling of clothes, but virtually no reverberance. Under such circumstances, adding reverb using active reverberation enhancement subsystem 222 to ambient sounds within the environment would reduce the credibility of the scene taking place. In other words, if the movie is showing a scene in a dry environment and someone watching the movie speaks, adding reverb to that ambient sound of speaking would produce a mismatch between the dry virtual acoustics presented by the movie and the real acoustics of the listening environment.

[0052] As such, reverberation unit 310 (and/or any other suitable component of system 300) may be connected (wirelessly and/or wired) to an audio source, and may receive an audio signal from the source. The reverberance of the audio signal may be measured, such as by determining the loudness of the signal over time and/or via any other suitable technique. Depending on the content of the audio signal, reverberation unit 310 may be configured such that an amount of reverberation added is proportional to (or otherwise selected based on) the measured amount of reverberation in the audio signal.

[0053] In some embodiments, whether and how much reverberation is applied by reverberation unit 310 may depend upon a listening environment in which system 300 is operating. The manner in which sound output from the reverberation unit 310, which is then output from one or more loudspeakers, propagates within the listening environment depends on characteristics of the listening environment (e.g., size, shape, types of surfaces present, etc.). Accordingly, knowledge of the natural reverberance of the environment may be used by reverberation unit 310 to produce a desired reverberance effect within the environment.

[0054] In some embodiments, one or more components of active reverb enhancement system 300 (e.g., reverberation unit 310), and/or a component of an audio system (e.g., systems 100 and/or 200) that comprises system 300, may measure reverberance of the listening environment. Such a measurement may occur when the system is first initialized, may occur periodically during system operation and/or may occur upon user request. The measurement may utilize one or more loudspeakers and one or more microphones of the system. For example, in system 200 depicted in FIG. 2, active reverberation enhancement subsystem 222 may make such a measurement by producing sound from loudspeakers 232 and/or 234, and by capturing a result of said sound production with microphone 212.

[0055] In some embodiments, measuring reverberance of a listening environment may comprise producing a predetermined measurement signal $x(t)$ from one or more loudspeakers. One or more microphones may be controlled to capture the measurement signal x(t) output from the loudspeaker(s). The captured microphone signal may be referred to as captured signal y(t), which corresponds to the measurement signal x(t) modified by an impulse response h(t) of the listening environment. In general, the impulse response is indicative of a history of direct and reflected sound at one position in the listening environment caused by an impulse emitted from a source at another position in the same listening environment. The impulse response may also sometimes be referred to as a room response or a transfer function in the frequency domain.

[0056] The measurement and captured signals x(t) and y(t), respectively, may be used to determine the impulse response h(t) of the listening environment. For example, in the time domain, the impulse response h(t) may be deconvolved from the captured signal y(t) and the measurement signal x(t). Alternatively, in the frequency domain the room response H(f) may be determined from a ratio of the frequency-domain measurement and captured signals, $H(\mathrm{f}) = Y(\mathrm{f}) \div X(\mathrm{f})$. A subsequent inverse frequency domain transform may then be applied to the room response H(f) to produce the time domain impulse response h(t). The reverberance of the listening environment may then be determined from the impulse response.

[0057] In some embodiments, an impulse response at one microphone position may be measured and used to represent the existing reverberation characteristic of the listening environment. In some embodiments, impulse responses at two or more positions in the listening environment may be determined (e.g., using two or more microphones, or by moving microphones between measurements), and an estimate of the reverberance of the listening environment may be determined.

[0058] According to some embodiments, a measurement signal may include a pseudorandom noise signal (e.g., a maximum length sequence (MLS), an inverse repeated sequence (IRS), etc.), a time- stretched pulse signal, a sine-sweep signal and/or any other signal suitable for determining an impulse response h(t) of the listening environment. In some embodiments, the measurement signal may be embedded in a predetermined audio signal (e.g., such as music), such that a listener may be substantially unaware of the measurement signal's presence in sound output from a loudspeaker.

[0059] According to some embodiments, a measurement of the interaural cross-correlation coefficient or a measure of binaural coherence may be measured in one or more locations within a given listening space. Adjustments to an audio system (e.g., audio system 100) may then be made based on such measurement(s) to produce a balanced IACC throughout the listening space. For instance, relative sound pressure levels (SPLs) of coherent and/or incoherent loudspeakers within the audio system may be adjusted.

[0060] Amplifier(s) 330 may comprise any one or more amplifiers, though may preferably include a low-noise amplifier. One example of a suitable amplifier includes a programmable two-channel D class amplifier such as the Behringer iNuke NU1000. Any number of amplifiers 330 may be connected to any number of loudspeakers.

[0061] According to some embodiments, DSP 320 may perform audio processing on the input audio signal before performing the above-described application of reverb by reverberation unit 310. Such processing may include, but is not limited to, equalization adjustments, loudness adjustment, frequency tuning, applying a compressor and/or expander, addition of delay or other effects, or combinations thereof.

[0062] FIG. 4 is a block diagram of an illustrative audio processing subsystem, according to some embodiments. According to some embodiments, audio processing subsystem 400 may be used as element 224 shown in FIG. 2. Audio processing subsystem 400 receives input from one or more audio sources, performs separation of components of the input audio based on the components' reverberation properties as described above via reverberation separation unit 410, and outputs sound to one or more loudspeakers via amplifier(s) 420.

[0063] According to some embodiments, reverberation separation unit 410 may perform dereverberation to identify a direct sound component of an audio signal. In some cases, the unit may additionally use the direct sound to identify remaining components remaining in the audio signal other than the direct sound. Illustrative processing techniques that may be used by reverberation separation unit 410 include, but are not limited to, dereverberation via spectral subtraction, dereverberation using channel inversion and equalization, automatic speech recognition, voice activity detection, acoustic echo cancellation (AEC), residual echo estimation, adaptive filter, double-talk detection, non-linear processing, or combinations thereof.

[0064] Amplifier(s) 420 may comprise any one or more amplifiers, though may preferably include a low-noise amplifier. Any number of amplifiers 420 may be connected to any number of loudspeakers.

[0065] FIGs. 5A-5C depict an illustrative apparatus for housing an audio system, according to some embodiments. FIG. 5A depicts a front face view of the housing, FIG. 5B depicts a front face view with the front panel removed, and FIG. 5C depicts a side view. Any number of components of the above-described systems may be incorporated within the housing 500, several of which are identified in the figures. In some embodiments, one or more subsystems, such as active reverberation enhancement subsystem 222 and/or audio processing subsystem 224, may be disposed within the depicted housing. In some embodiments, one or more of such subsystems may be connected to components within the housing via any number of wired or wireless connections.

[0066] In the example of FIG. 5A, an upper section of the panel includes a circular portion cut out of the diffuse radiator loudspeaker 520 to produce the direct radiator loudspeaker 540. The panel within the cut out portion that acts as direct radiator loudspeaker 540 may have been stiffened relative to the panel of diffuse radiator loudspeaker 520 so that it functions as a coherent radiation source. In some embodiments, the direct radiator loudspeaker 540 may include a collar to reduce air-turbulence and/or to improve bass response. A gap between diffuse radiator loudspeaker 520 and direct radiator loudspeaker 540 may, for example, be around 2mm.

[0067] In the example of FIG. 5B, a support 560 provides structure sufficient to hold transducers (and possibly wires connected to those transducers) of the loudspeakers 520, 530 and 540. Transducers 561, 562 and 563 correspond to loudspeakers 520, 530 and 540, respectively.

[0068] According to some embodiments, diffuse radiator loudspeakers 520 and/or 530 may be configured to produce incoherent sound. For instance, either or both speakers may exhibit an IACC coefficient of below 0.7, below 0.5, etc.

[0069] The above-described embodiments of the technology described herein can be implemented in any of numerous ways. For example, the embodiments may be implemented using hardware, software or a combination thereof. When implemented in software, the software code can be executed on any suitable processor or collection of processors, whether provided in a single computer or distributed among multiple computers. Such processors may be implemented as integrated circuits, with one or more processors in an integrated circuit component, including commercially available integrated circuit components known in the art by names such as CPU chips, GPU chips, microprocessor, microcontroller, or co-processor. Alternatively, a processor may be implemented in custom circuitry, such as an ASIC, or semi-custom circuitry resulting from configuring a programmable logic device. As yet a further alternative, a processor may be a portion of a larger circuit or semiconductor device, whether commercially available, semi-custom made or custom made. As a specific example, some commercially available microprocessors have multiple cores such that one or a subset of those cores may constitute a processor, although a processor may be implemented using circuitry in any suitable format.

[0070] An illustrative implementation of a computer system 600 that may be used to perform aspects of acoustic reverberance control as described herein is shown in FIG. 6. The computer system 600 may include one or more processors 610 and one or more non-transitory computer-readable storage media or storage devices (e.g., memory 620 and one or more non-volatile storage media 630). The processor 610 may control writing data to and reading data from the memory 620 and the non-volatile storage device 630 in any suitable manner, as the aspects of the invention described herein are not limited in this respect. To perform the functionality and/or techniques described herein, the processor 610 may execute one or more instructions stored in one or more computer-readable storage media (e.g., the memory 620, storage media, etc.), which may serve as non-transitory computer-readable storage media storing instructions for execution by the processor 610.

[0071] In connection with techniques for acoustic reverberance control as described herein, code used to, for example, perform reverb processing upon an audio signal, separate components of an audio signal based on their reverberance, etc. may be stored on one or more computer-readable storage media of computer system 600. Processor 610 may execute any such code to provide any techniques for acoustic reverberance control as described herein. Any other software, programs or instructions described herein may also be stored and executed by computer system 600. It will be appreciated that computer code may be applied to any aspects of methods and techniques described herein. For example, computer code may be applied to any reverberation and/or dereverberation algorithm described herein or otherwise.

[0072] Various inventive concepts may be embodied as at least one non-transitory computer readable storage medium (e.g., a computer memory, one or more floppy discs, compact discs, optical discs, magnetic tapes, flash memories, circuit configurations in Field Programmable Gate Arrays or other semiconductor devices, etc.) or a computer readable storage device encoded with one or more programs that, when executed on one or more computers or other processors, implement some of the various embodiments of the present invention. The non-transitory computer-readable medium or media may be transportable, such that the program or programs stored thereon may be loaded onto any computer resource to implement various aspects of the present invention as discussed above.

[0073] The terms “program,” “software,” and/or “application” are used herein in a generic sense to refer to any type of computer code or set of computer-executable instructions that can be employed to program a computer or other processor to implement various aspects of embodiments as discussed above. Additionally, it should be appreciated that according to one aspect, one or more computer programs that when executed perform methods of one or more embodiments described herein need not reside on a single computer or processor, but may be distributed in a modular fashion among different computers or processors to implement various aspects of the present invention.

[0074] Having herein described several embodiments, several advantages of embodiments of the present application should be apparent. One advantage is that embodiments may allow for improvement of the acoustics of a listening space without complex configuration and setup of multiple speakers. In particular, propagating reverberance using incoherent radiators may be relatively straightforward compared with propagating reverberance using coherent radiators, which typically require both careful placement of multiple units and intensive calculations to produce the desired effect.

[0075] Another advantage of embodiments of the present application is that including microphones within an audio system might normally be expected to cause the audio system to be highly susceptible to feedback, but this may be mitigated by the nature of incoherent loudspeakers.

[0076] Aspects of the techniques of acoustic reverberance control described herein may be used in live musical performances, and in particular in an environment considered to be "dry." Concert halls typically are chosen for musical performances due to their natural propensity for reverberating sound and producing a pleasing result to listeners within the room. However, techniques described herein may allow a space not typically used for musical performance due to its size and/or constituent features to be used effectively in musical performance. For instance, instruments may be played in proximity to one or more microphones of the systems described herein (e.g., system 100 and/or system 200) and reverberant sound may be produced using the techniques described herein from the sound of the instruments captured by the microphone(s).

[0077] In use cases in which a system like system 500 is positioned close to musical instruments being played, it might generally be expected that sound produced from the loudspeakers would cause feedback between the microphone and the speakers. However, by producing incoherent sound from the speakers feedback may be avoided, and the sound of the instruments may be produced from the system having both the sound content and physical characteristics of naturally reverberant sound that might normally require a large concert hall to produce. In some use cases, a beneficial positioning of a system like system 500 may be on the walls or otherwise adjacent to performers, may be behind, above and/or in one or more aisles between audience members, and/or may not include loudspeakers or microphones in proximity to any of the musicians. In preferred use cases, an audio system such as system 500 may be placed between performers and audience members.

[0078] Having thus described several aspects of at least one embodiment of this invention, it is to be appreciated that various alterations, modifications, and improvements will readily occur to those skilled in the art.

[0079] Such alterations, modifications, and improvements are intended to be part of this disclosure, and are intended to be within the spirit and scope of the invention. Further, though advantages of the present invention are indicated, it should be appreciated that not every embodiment of the technology described herein will include every described advantage. Some embodiments may not implement any features described as advantageous herein and in some instances one or more of the described features may be implemented to achieve further embodiments. Accordingly, the foregoing description and drawings are by way of example only.

[0080] Various inventive concepts may be embodied as one or more methods, of which examples have been provided. The acts performed as part of a method may be ordered in any suitable way. Accordingly, embodiments may be constructed in which acts are performed in an order different than illustrated, which may include performing some acts simultaneously, even though shown as sequential acts in illustrative embodiments.

[0081] Use of ordinal terms such as “first,” “second,” “third,” etc., in the claims to modify a claim element does not by itself connote any priority, precedence, or order of one claim element over another or the temporal order in which acts of a method are performed, but are used merely as labels to distinguish one claim element having a certain name from another element having a same name (but for use of the ordinal term) to distinguish the claim elements.

[0082] Also, the phraseology and terminology used herein is for the purpose of description and should not be regarded as limiting. The use of “including,” “comprising,” or “having,” “containing,” “involving,” and variations thereof herein, is meant to encompass the items listed thereafter and equivalents thereof as well as additional items.

[0083] What is claimed is:

CLAIMS

1. An audio system, comprising:

at least one microphone configured to capture ambient sound within a listening space;

a diffuse radiator loudspeaker configured to produce incoherent sound waves; and

a reverberation processing unit configured to:

apply reverberation to at least a portion of ambient sound captured by the at least one microphone, thereby producing modified sound; and

output the modified sound into the listening space via the diffuse radiator loudspeaker.

2. The audio system of claim 1, wherein the diffuse radiator loudspeaker exhibits an interaural cross-correlation (IACC) coefficient of less than 0.5.

3. The audio system of claim 1, wherein the reverberation processing unit is further configured to output the ambient sound captured by the at least one microphone synchronously with the output of the modified sound.

4. The audio system of claim 3, further comprising a subwoofer, and wherein the output of the ambient sound is performed at least in part by the subwoofer.

5. The audio system of claim 1, wherein the reverberation processing unit is configured to determine the reverberation based at least in part on one or more reverberation characteristics of the listening space.

6. The audio system of claim 5, wherein the reverberation processing unit is further configured to:

output an audible measurement signal from the diffuse radiator loudspeaker and/or from another loudspeaker; and

determine the one or more reverberation characteristics of the listening space based on ambient sound captured by the at least one microphone while the audible measurement signal is being output.

7. The audio system of claim 6, wherein the audible measurement signal comprises one or more of: a pseudorandom noise signal, a time-stretched pulse signal and a sine-sweep signal.

8. The audio system of claim 1, further comprising a digital signal processing unit configured to perform processing of the ambient sound captured by the at least one microphone and to output a result of the processing to the reverberation processing unit.

9. The audio system of claim 1, wherein the at least one microphone includes an omnidirectional microphone.

10. The audio system of claim 1, wherein the diffuse radiator loudspeaker is a distributed mode loudspeaker.

11. The audio system of claim 1, further comprising:

an audio source configured to output an audio signal; and

an audio processing unit configured to:

receive the audio signal; and

separate the audio signal into a direct sound portion and an early reflections portion.

12. The audio system of claim 11, wherein the audio processing unit is further configured to output the early reflections portion to the diffuse radiator loudspeaker.

13. The audio system of claim 11, wherein the audio processing unit is further configured to output the early reflections portion to a second diffuse radiator loudspeaker.

14. The audio system of claim 11, further comprising a direct radiator loudspeaker, and wherein the audio processing unit is further configured to output the direct sound portion to the direct radiator loudspeaker.

15. The audio system of claim 11, wherein the audio processing unit is further configured to apply a delay to the early reflections portion.

16. The audio system of claim 11, wherein the early reflections portion consists of sound originating between 5 ms and 80 ms after initiation of sound of the direct sound portion.

17. A method, comprising:

capturing ambient sound within a listening space using at least one microphone;

applying reverberation to at least a portion of the ambient sound captured by the at least one microphone, thereby producing modified sound; and

outputting the modified sound into the listening space from an incoherent diffuse radiator loudspeaker.

18. The method of claim 17, further comprising outputting the ambient sound captured by the at least one microphone synchronously with said outputting of the modified sound.

19. The method of claim 17, wherein the reverberation applied is based at least in part on one or more reverberation characteristics of the listening space.

20. The method of claim 19, further comprising:

outputting an audible measurement signal from the diffuse radiator loudspeaker and/or from another loudspeaker; and

determining the one or more reverberation characteristics of the listening space based on ambient sound captured by the at least one microphone while the audible measurement signal was being output.

21. The method of claim 20, wherein the audible measurement signal comprises one or more of: a pseudorandom noise signal, a time-stretched pulse signal and a sine-sweep signal.

22. The method of claim 17, further comprising:

separating an audio source signal into a direct sound portion and an early reflections portion; and

outputting the direct sound portion to a direct radiator loudspeaker.

23. The method of claim 22, further comprising outputting the early reflections portion to a second diffuse radiator loudspeaker.

24. The method of claim 22, further comprising applying a delay to the early reflections portion.

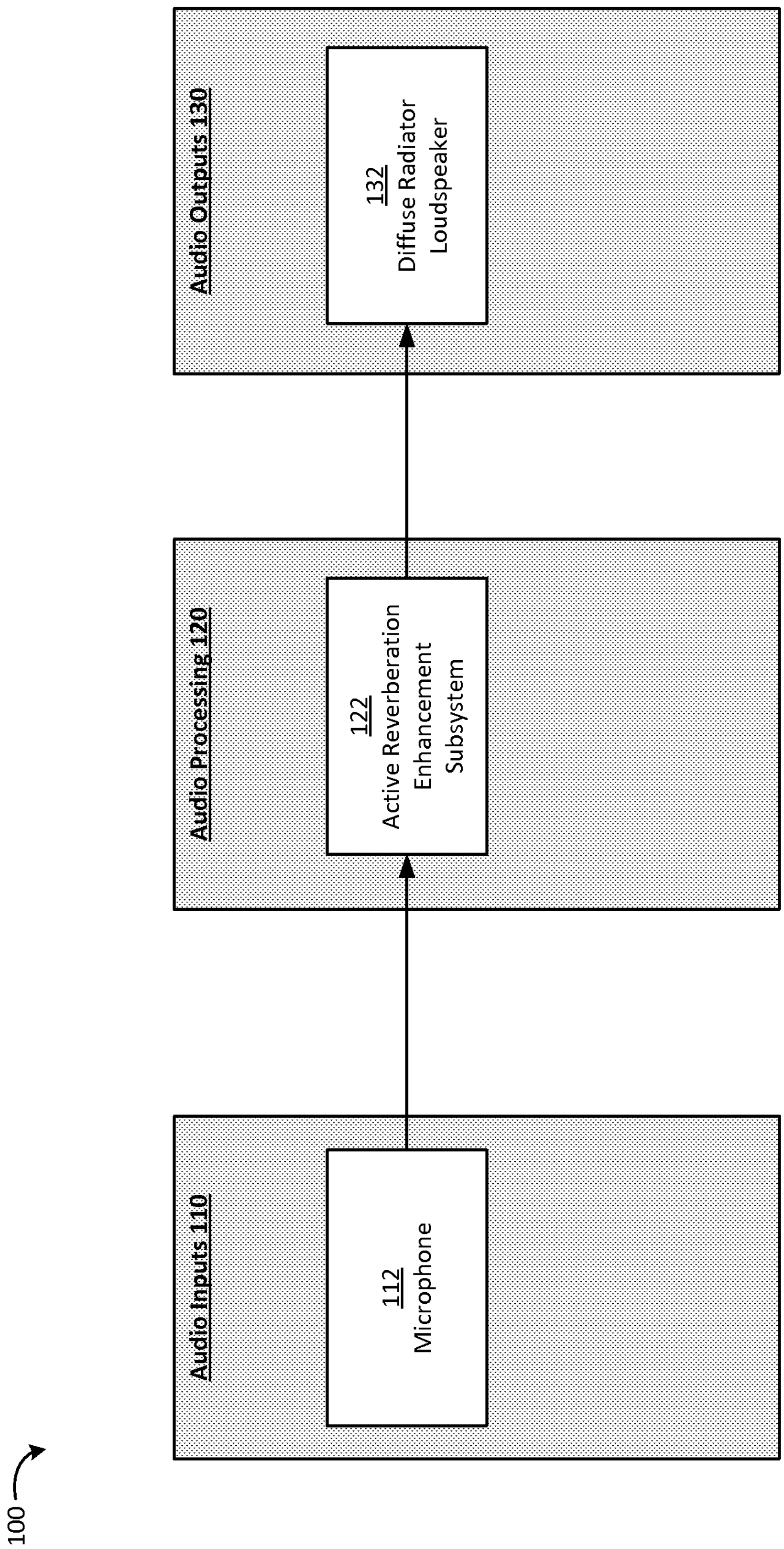

100
Audio Inputs 110
112
Microphone
Audio Processing 120
122
Active Reverberation
Enhancement
Subsystem
Audio Outputs 130
132
Diffuse Radiator
Loudspeaker

FIG. 1

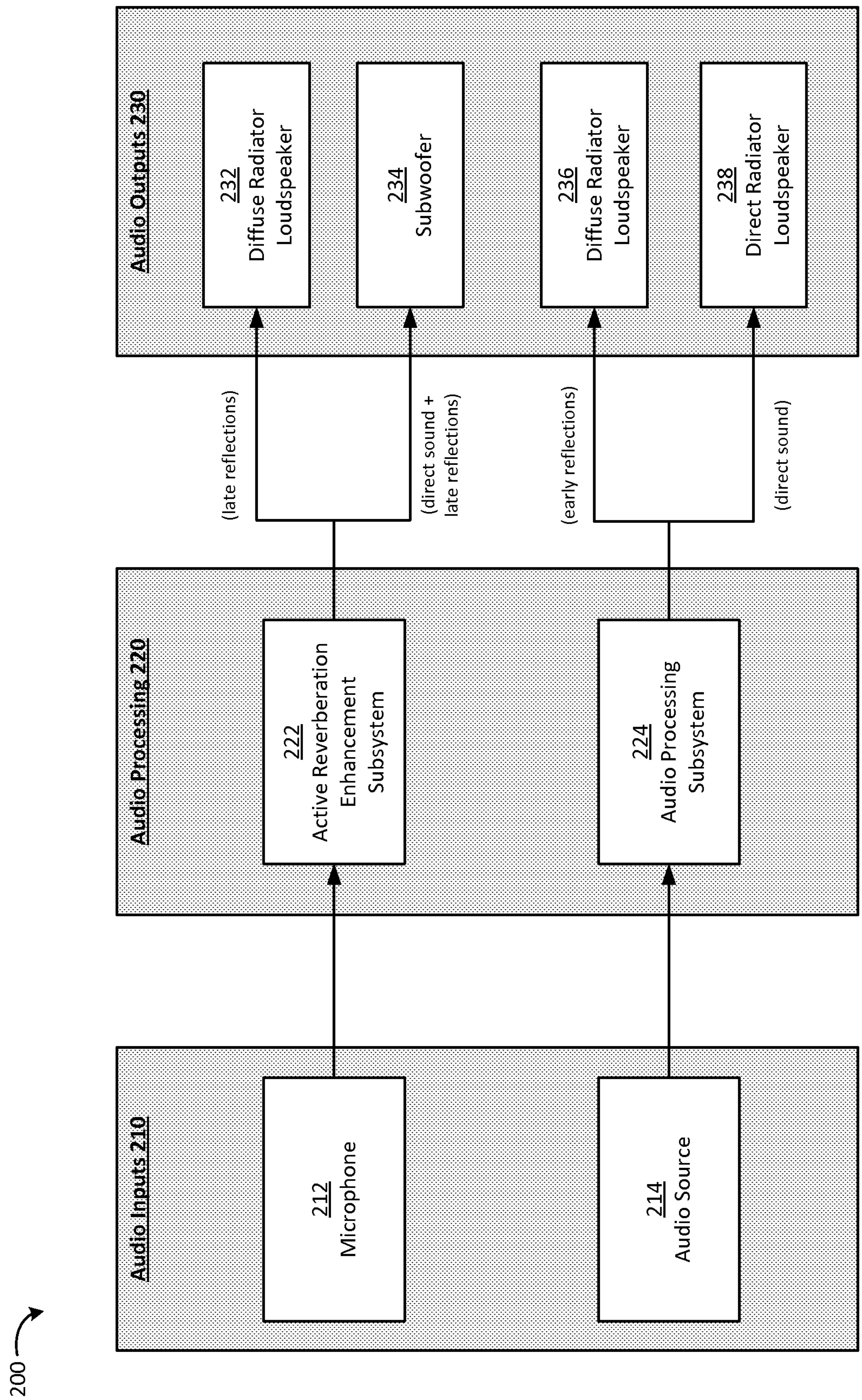

200
Audio Inputs 210
212
Microphone
214
Audio Source
Audio Processing 220
222
Active Reverberation
Enhancement
Subsystem
224
Audio Processing
Subsystem
(late reflections)
(direct sound +
late reflections)
(early reflections)
(direct sound)
Audio Outputs 230
232
Diffuse Radiator
Loudspeaker
234
Subwoofer
236
Diffuse Radiator
Loudspeaker
238
Direct Radiator
Loudspeaker

FIG. 2

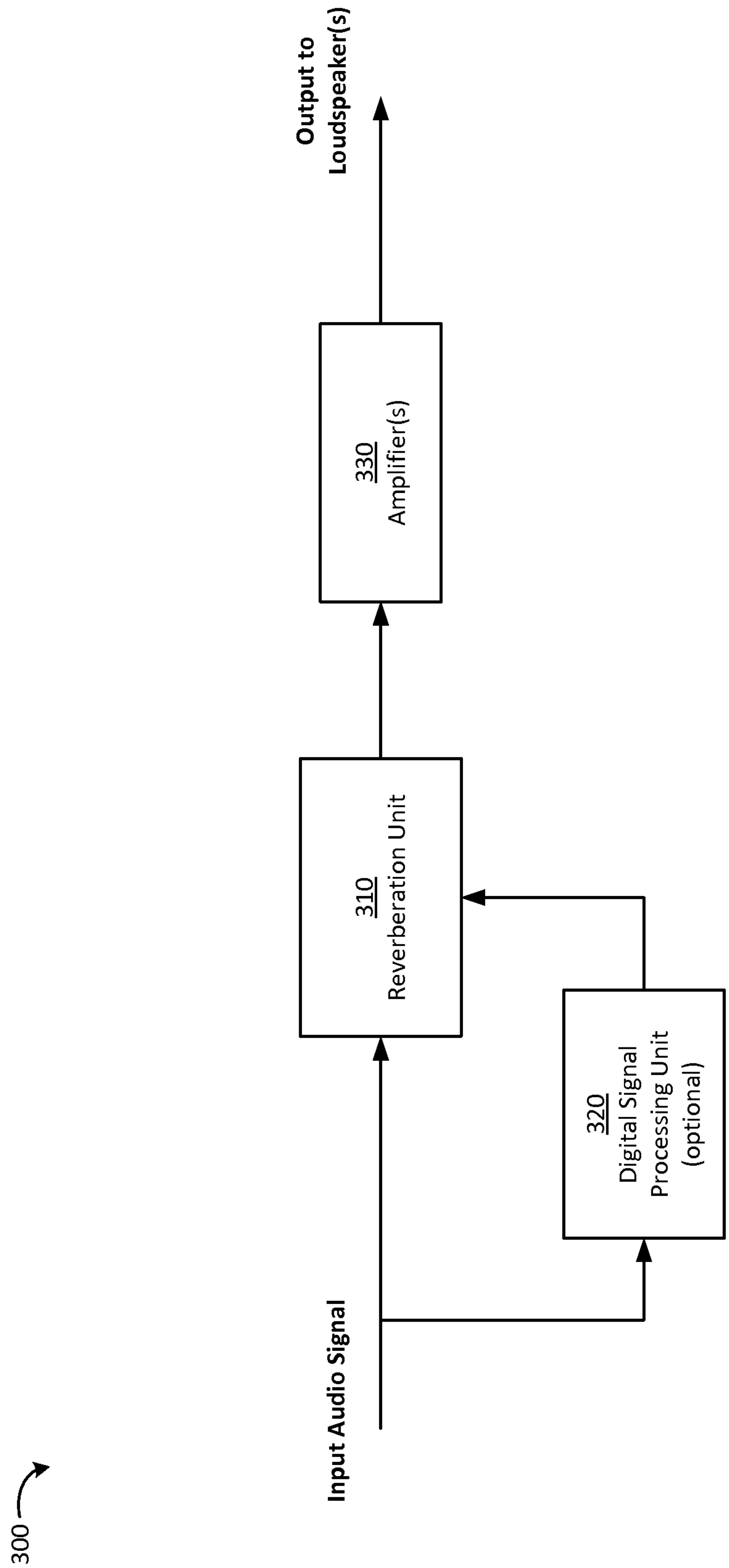

300
Input Audio Signal
310
Reverberation Unit
320
Digital Signal Processing Unit (optional)
330
Amplifier(s)
Output to Loudspeaker(s)

FIG. 3

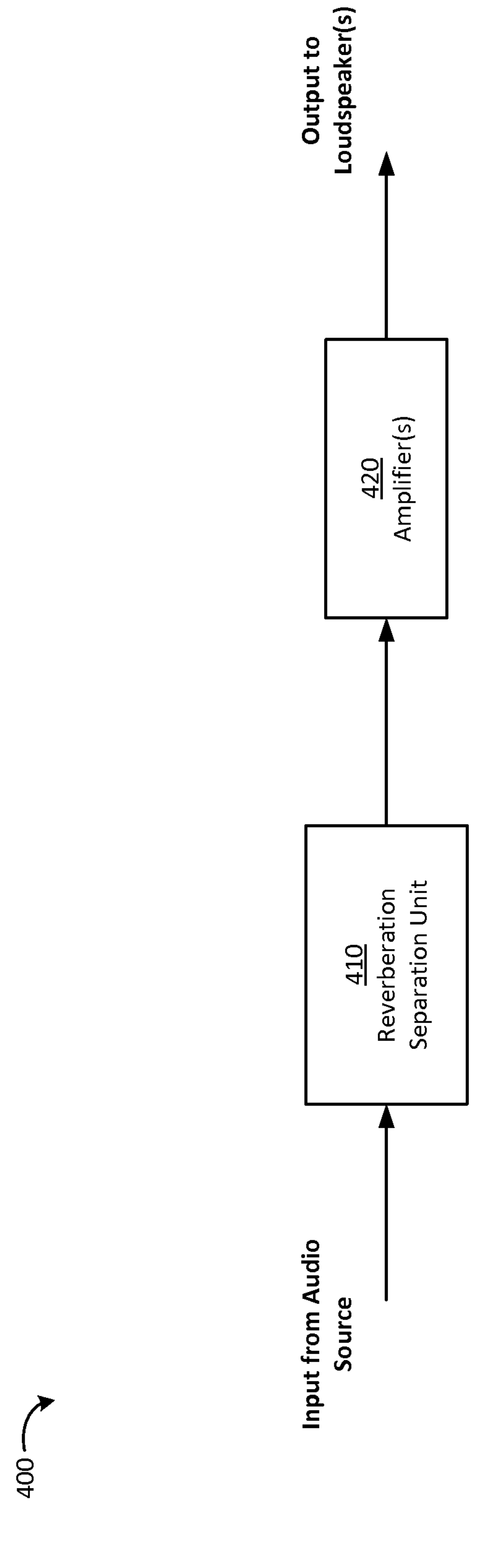

400
Input from Audio Source
410
Reverberation Separation Unit
420
Amplifier(s)
Output to Loudspeaker(s)

FIG. 4

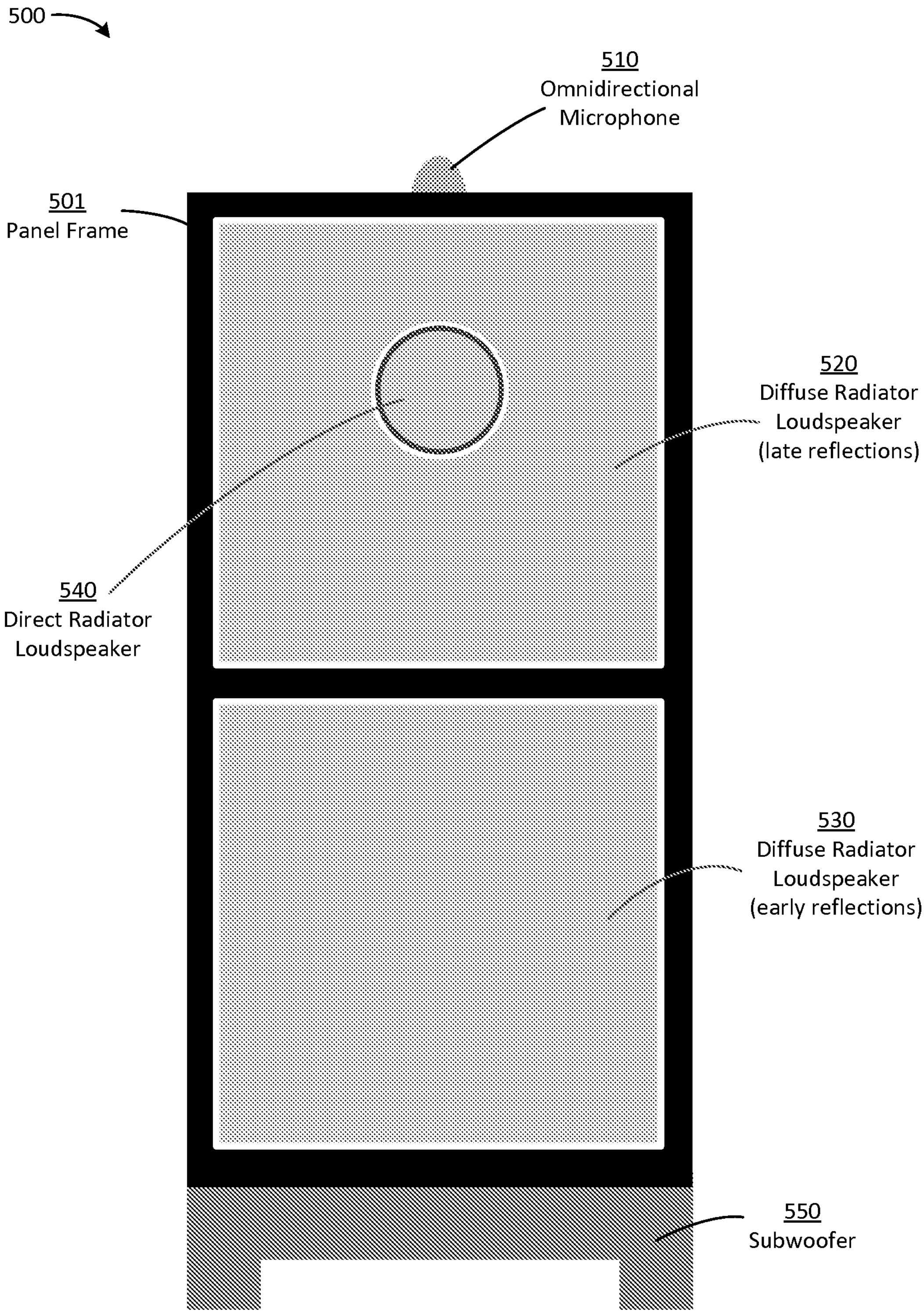

500
510
Omnidirectional
Microphone
501
Panel Frame
520
Diffuse Radiator
Loudspeaker
(late reflections)
540
Direct Radiator
Loudspeaker
530
Diffuse Radiator
Loudspeaker
(early reflections)
550
Subwoofer

FIG. 5A

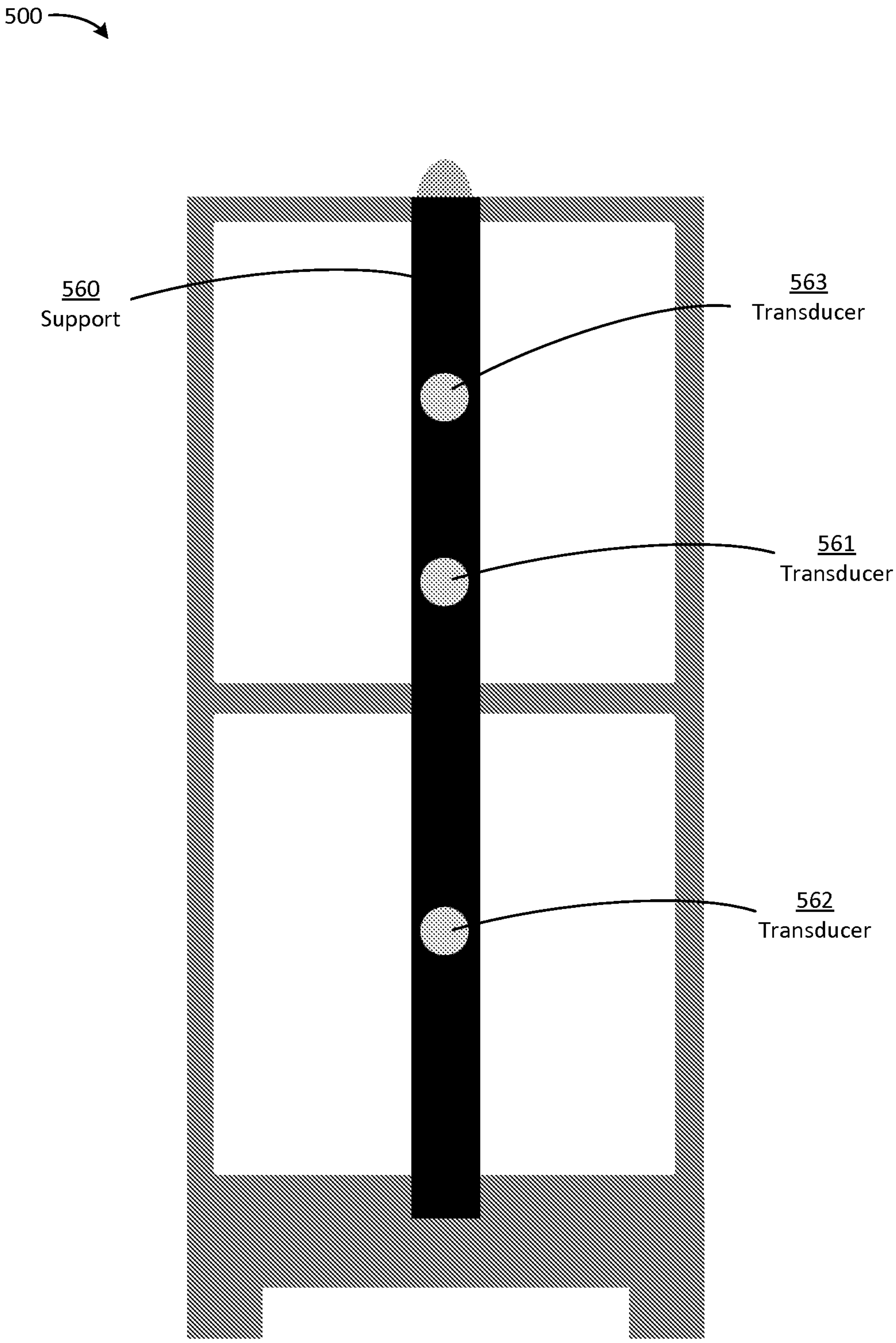

500
560
Support
563
Transducer
561
Transducer
562
Transducer

FIG. 5B

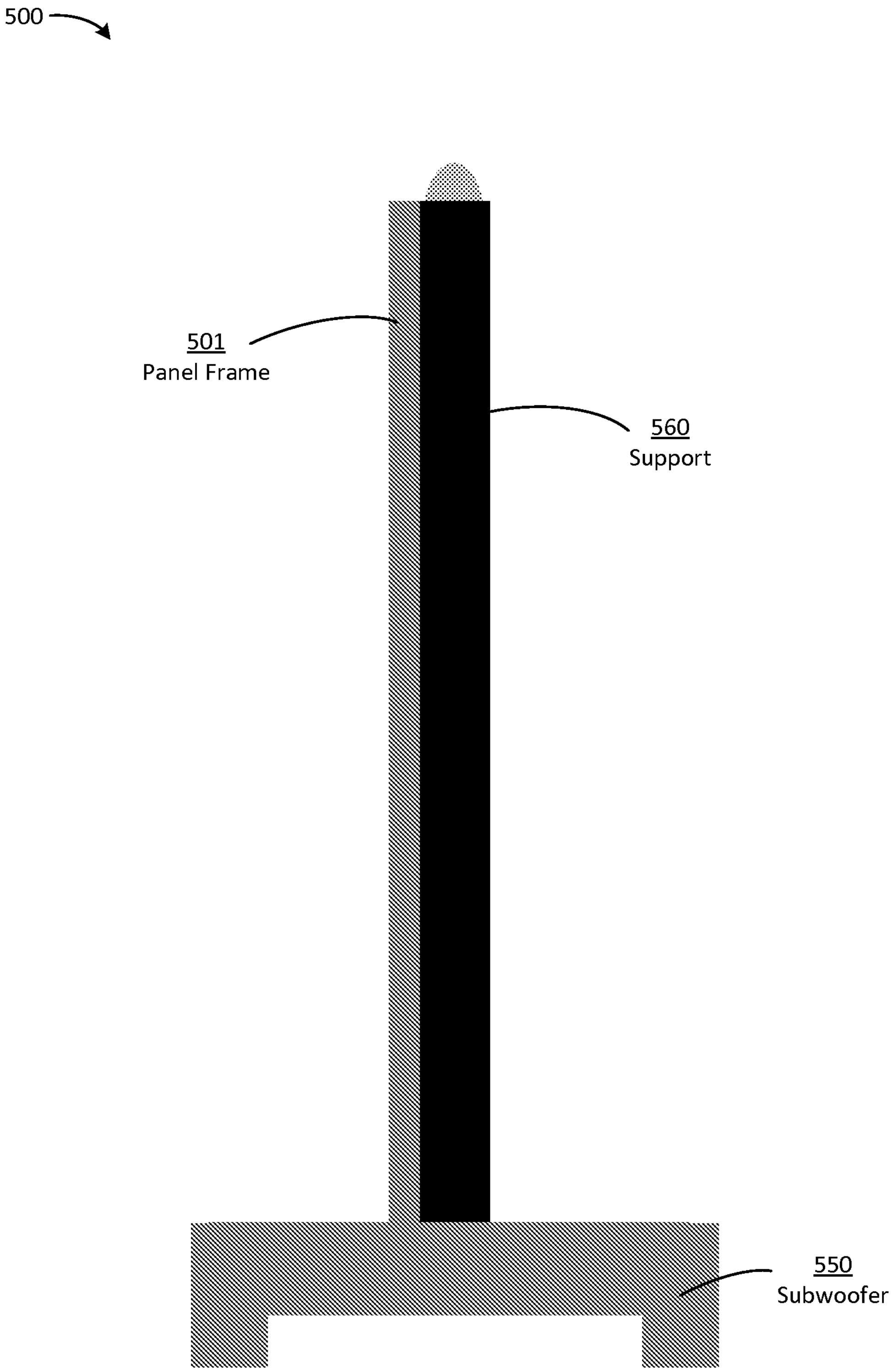
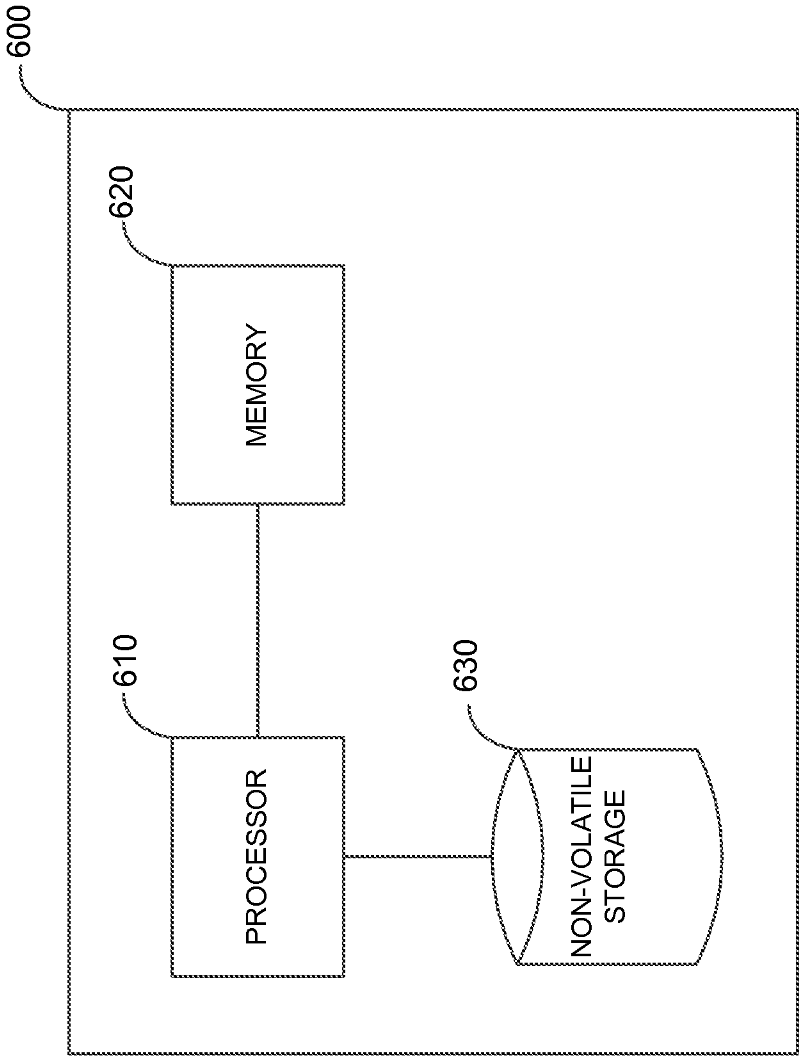


FIG. 5C

FIG. 6



INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2015/002019

A. CLASSIFICATION OF SUBJECT MATTER
INV. H04S7/00
ADD. H04R7/04

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H04R H04S

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	Yasuhiko Nagatomo ET AL: "Variable reflection acoustic wall system by active sound radiation", Acoustical Science and Technology, 1 March 2007 (2007-03-01), page 84, XP055248047, Tokyo DOI: 10.1250/ast.28.84] Retrieved from the Internet: URL:https://www.jstage.jst.go.jp/article/ast/28/2/28_2_84/_pdf [retrieved on 2016-02-05] Sections 2, 3.1; figures 1, 7, 8 -----	1-4,9, 17,18

-/--

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
11 February 2016	19/02/2016

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Joder, Cyril

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2012/275613 A1 (SOULODRE GILBERT ARTHUR JOSEPH [CA]) 1 November 2012 (2012-11-01) paragraphs [0032], [0087], [0119] - [0178]; figures 2, 9-11	1-24
Y	US 2006/023898 A1 (KATZ SHELLEY [GB]) 2 February 2006 (2006-02-02) paragraphs [0002], [0030], [0091] - [0111], [0133] - [0142]; figures 2, 4, 8, 9, 12	1-24
Y	Hugh Alexander Hopper: "Reverberation Enhancement for Small Rooms", Doctoral Thesis, 1 January 2012 (2012-01-01), XP055247989, Retrieved from the Internet: URL:http://eprints.soton.ac.uk/348944/1.hasCoversheetVersion/HAHopper_Thesis.pdf [retrieved on 2016-02-05] page 24	1-24

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2012275613 A1	01-11-2012	CN 101454825 A	10-06-2009
		CN 103402169 A	20-11-2013
		EP 2064699 A1	03-06-2009
		JP 4964943 B2	04-07-2012
		JP 5406956 B2	05-02-2014
		JP 5635669 B2	03-12-2014
		JP 2009531722 A	03-09-2009
		JP 2012145962 A	02-08-2012
		JP 2014052654 A	20-03-2014
		US 2008069366 A1	20-03-2008
		US 2008232603 A1	25-09-2008
		US 2012063608 A1	15-03-2012
		US 2012275613 A1	01-11-2012
		WO 2008034221 A1	27-03-2008
US 2006023898 A1	02-02-2006	NONE	