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

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
22 August 2024 (22.08.2024)

WIPO | PCT

(10) International Publication Number
WO 2024/173704 A1

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

(21) International Application Number:
PCT/US2024/016014

(22) International Filing Date:
15 February 2024 (15.02.2024)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
63/446,774 17 February 2023 (17.02.2023) US
63/613,318 21 December 2023 (21.12.2023) US

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(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, CV, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IQ, IR, IS, IT, JM, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, MG, MK, MN, MU, 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, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, WS, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, CV, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SC, 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, ME, MK, MT, NL, NO, PL, PT, RO, RS, SE,

(54) Title: GENERATION OF PERSONALIZED HEAD-RELATED TRANSFER FUNCTIONS (PHRTFS)

(57) Abstract: A method for efficiently generating personalized head-related transfer functions, pHRTFs, for a user of a media playback device including obtaining a default HRTF related to one or several default parameters, each default parameter being associated with a specific human feature, determining at least one personalization parameter, each personalization parameter being associated with one of the specific human features of the user, and modifying the default HRTF based on a relationship between the at least one personalization parameter and corresponding default parameter(s), to determine the pHRTFs.

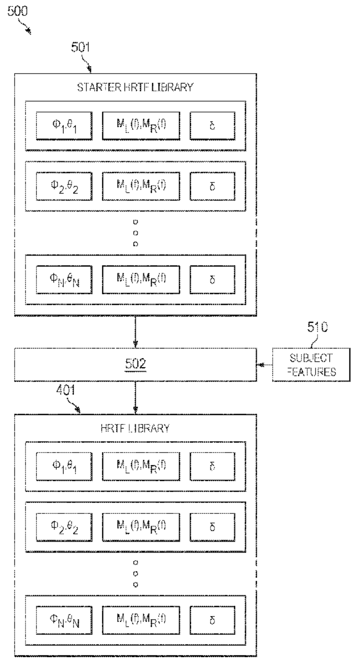

FIG. 5

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[Continued on next page]

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))*

GENERATION OF PERSONALIZED HEAD-RELATED TRANSFER FUNCTIONS (PHRTFS)

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to United States Provisional Patent Application No. 63/446,774 filed 17 February 2023; and United States Provisional Patent Application No. 63/613,318 filed 21 December 2023, which are incorporated herein by reference in their entireties.

FIELD

[0002] The present invention relates to a generation of head-related transfer functions (HRTFs).

BACKGROUND

[0003] Head Related Transfer Functions (HRTFs) are a set of functions describing how human ears receive sound from sources at varying directions of arrival. The functions typically describe linear filtering processes that reflect the acoustic effect of the ears, head and torso on incoming sound waves.

[0004] HRTFs may be defined in many ways, including as time-domain impulse responses or as frequency-domain responses. HRTFs are typically grouped in pairs, to provide a response for each ear. An HRTF filter pair may be used to provide a listener with an experience that mimics the sound (at each ear) that would occur when the audio signal was presented from a particular direction of arrival. Different HRTF filter pairs will produce the illusion of differing sound-source directions.

[0005] A user's anatomy may affect how sound is received at the ears of the user, due to the diffraction and occlusion of the incident soundwaves on the user's body. There is therefore a general desire to tailor HRTFs to a particular individual. Such HRTFs are herein referred to as personalized HRTFs (pHRTFs).

SUMMARY

[0006] Although pHRTFs may be obtained through experimental measurement procedures, or modelled using personalized information pertaining to the user, this is often a complex and time-consuming process.

[0007] It is an object of the present invention to facilitate generation of pHRTFs.

[0008] According to a first aspect of the invention, this and other objects are achieved by a method for generating a set of personalized head-related transfer functions, pHRTFs, for a user of a media playback device comprising obtaining a default HRTF set related to one or several default parameters, each default parameter being associated with a specific human feature, determining at least one personalization parameter, each personalization parameter being associated with one of the specific human features of the user, and modifying the default HRTF set based on a relationship between the at least one personalization parameter and corresponding default parameter(s), to determine the set of pHRTFs.

[0009] The modifying of the default HRTF set may include e.g. frequency remapping, frequency scaling, and angular shift.

[0010] The present invention provides an efficient way to modify and personalize HRTFs, based on a few well-defined parameters. By determining default parameters for the default HRTF set, and comparing these with personalization parameters specific for the user, a modification of the default HRTF set can be done according to pre-determined relationships.

[0011] The default parameters may be physical, such as head size, ear size and ear tilt angle. However, at least one of the default parameters may be associated with a specific non-physical feature, wherein the default parameters include a default value, and wherein modifying the default HRTF set includes adapting the default HRTFs to compensate for a difference between a determined value corresponding to the specific non-physical feature of the user and the default value.

[0012] The default HRTF set may be selected from a plurality of such sets, based on one or more personalization parameters associated with non-physical features of the user. Such non-physical features may be demographic properties, such as age, gender, birth sex, geographic location, nationality, ethnicity. By selecting an appropriate default HRTF set, the personalization process can be made more robust and reliable.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] The present invention will be described in more detail with reference to the appended drawings, showing currently preferred embodiments of the invention.

[0014] Figure 1 shows a user with a set of headphones.

[0015] Figure 2 is a diagram illustrating a Cartesian coordinate system in accordance with some embodiments.

[0016] Figure 3 is a diagram showing a sound incident at the left ear of a subject, in accordance with some embodiments.

[0017] Figure 4 is a diagram showing the determining of an HRTF from an HRTF Library, in accordance with some embodiments.

[0018] Figure 5 is a diagram showing modification of a Starter HRTF Library to form a new HRTF Library, in accordance with some embodiments.

[0019] Figure 6 is a diagram showing details of the direction of arrival of an incident wave at an ear, in accordance with some embodiments.

[0020] Figure 7 is a diagram showing details of the direction of arrival of an incident wave at a rotated ear, in accordance with some embodiments.

[0021] Figure 8 is a diagram showing size variation between ears, in accordance with some embodiments.

[0022] Figure 9 is a plot showing frequency response of HRTFs, in accordance with some embodiments.

[0023] Figure 10 is a plot showing inter-aural time delay between left and right ear HRTFs, in accordance with some embodiments.

[0024] Figure 11 is a diagram showing modification of one delay-separated HRTF filter, in accordance with some embodiments.

[0025] Figure 12 is a flow diagram illustrating a process for generating personalize HRTFs using an electronic device, in accordance with some embodiments.

DETAILED DESCRIPTION

[0026] With reference to Fig. 1, a user 1 listens to audio played back from a media player 2, using a set of headphones 3. For binaural rendering of the audio, head related transfer functions (HRTFs) are used.

[0027] Described herein are techniques related to processing of an HRTF Library to produce a new HRTF Library that is adapted to be suitable for an individual listener. The adapted HRTFs are referred to as personalized HRTFS, or pHRTFs. In the following description, for purposes of explanation, numerous examples and specific details are set forth in order to provide a thorough understanding of the present disclosure.

[0028] Systems and methods disclosed in the present application may be implemented as software, firmware, hardware or a combination thereof. In a hardware implementation, the division of tasks does not necessarily correspond to the division into physical units; to the contrary, one physical component may have multiple functionalities, and one task may be carried out by several physical components in cooperation.

[0029] The computer hardware may for example be a server computer, a client computer, a personal computer (PC), a tablet PC, a set-top box (STB), a personal digital assistant (PDA), a cellular telephone, a smartphone, an XR device (e.g., an AR or VR headset), a web appliance, a network router, switch or bridge, or any machine capable of executing instructions (sequential or otherwise) that specify actions to be taken by that computer hardware. Further, the present disclosure shall relate to any collection of computer hardware that individually or jointly execute instructions to perform any one or more of the concepts discussed herein.

[0030] Certain or all components may be implemented by one or more processors that accept computer-readable (also called machine-readable) code containing a set of instructions that when executed by one or more of the processors carry out at least one of the methods described herein. Any processor capable of executing a set of instructions (sequential or otherwise) that specify actions to be taken are included. Thus, one example is a typical processing system (i.e. a computer hardware) that includes one or more processors. Each processor may include one or more of a CPU, a graphics processing unit, and a programmable DSP unit. The processing system further may include a memory subsystem including a hard drive, SSD, RAM and/or ROM. A bus subsystem may be included for communicating between the components. The software may reside in the memory subsystem and/or within the processor during execution thereof by the computer system.

[0031] The one or more processors may operate as a standalone device or may be connected, e.g., networked to other processor(s). Such a network may be built on various different network protocols, and may be the Internet, a Wide Area Network (WAN), a Local Area Network (LAN), or any combination thereof.

[0032] The software may be distributed on computer readable media, which may comprise computer storage media (or non-transitory media) and communication media (or transitory media). As is well known to a person skilled in the art, the term computer storage media includes both volatile and non-volatile, removable and non-removable media implemented in any method or technology for storage of information such as computer readable instructions, data structures, program modules or other data. Computer storage media includes, but is not limited to, physical (non-transitory) storage media in various forms, such as EEPROM, flash memory or other memory technology, CD-ROM, digital versatile disks (DVD) or other optical disk storage, magnetic cassettes, magnetic tape, magnetic disk storage or other magnetic storage devices, or any other medium which can be used to store the desired information and which can be accessed by a computer. Further, it is well known to the skilled person that communication media (transitory) typically embodies computer readable instructions, data structures, program modules or other data in a modulated data signal such as a carrier wave or other transport mechanism and includes any information delivery media.

[0033] Head Related Transfer Function (HRTF) filters may be used to process audio signals to produce binaural audio signals, so as to provide a listener the illusion of sounds arriving from prescribed directions of arrival. A direction of arrival may be defined in terms of an (x, y, z) unit vector (where the Cartesian coordinates are defined in Fig. 2). According to Fig. 2, a coordinate frame is located with its origin approximately at the center of the listener's head with the X axis 101 pointing forward (in the direction of the listener's nose), the Y axis 102 pointing to the listener's left, and the Z axis 103 pointing upward through the top of the listener's head.

[0034] In one embodiment, the direction of arrival of a sound source may be defined according to a lateral-polar coordinate system, whereby the angles (ϕ, θ) refer to the lateral angle ϕ (the angle from the median plane, x-z), and the elevation angle θ (the angle measured as a rotation around the inter-aural y-axis).

[0035] The (x, y, z) unit vector (in Cartesian coordinates) is related to the lateral-polar angles as follows:

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} \cos\phi\cos\theta \\ \sin\phi \\ \cos\phi\sin\theta \end{pmatrix} \quad (1)$$

[0036] Fig. 3 shows a sound, emitted by an object 5, incident at the left ear 4 of the user 1 from a direction 6. The elevation angle θ defines the angular displacement of the direction 120, relative to the forward-facing X-axis 101, as a rotation around the Y-axis (102 in Fig. 2).

[0037] An HRTF filter is defined as a frequency response, according to the following nomenclature:

$$\mathbf{HRTF}_{ear,\phi,\theta}^{id}(f) \in \mathbb{C} \quad (2)$$

where the frequency response is a complex value (indicative of magnitude and phase), and:

$$\begin{aligned} id &= \text{identity of the HRTF set or the subject ID} \\ ear &= \text{ear } (L \text{ or } R) \\ \phi &= \text{lateral angle of source (angle from median plan)} \\ \theta &= \text{elevation angle of source} \\ f &= \text{frequency} \end{aligned} \quad (3)$$

[0038] Alternatively, the nomenclature may be simplified to refer to various groupings of related HRTFs . For example:

$$\begin{aligned} \mathbf{HRTF}_{\phi,\theta}^{id}(f) &= \text{A pair of (L,R) ear HRTFs} \\ \mathbf{HRTF}^{id}(f) &= \text{A complete HRTF set (e.g., HRTF pairs for all DOAs)} \end{aligned} \quad (4)$$

[0039] In further examples of the terminology, the id super-script may be used to define various groupings of HRTFs with particular characteristics , making use of descriptive IDs such as:

$\boldsymbol{HRTF}^{\boldsymbol{default}}(f)$ = HRTFs intended for general use (e.g., a set of HRTFs not adapted to a specific individual)

$$\boldsymbol{HRTF}^{tony}(f) = \text{HRTFs adapted for subject Tony} \quad (5)$$

$$\boldsymbol{HRTF}^{big\,heads}(f) = \text{HRTFs adapted for subjects with larger heads}$$

$$\boldsymbol{HRTF}^{r=7cm}(f) = \text{HRTFs adapted for subjects with a ~7cm head radius}$$

[0040] In some embodiments, HRTF filters, for the left and right ear, include a time-delay difference (Interaural Time Difference, or ITD).

[0041] In some embodiments, each Left/Right pair (e.g., corresponding to $\mathbf{HRTF}^{id}_{L,\phi_n,\theta_n}(f)$ and $\mathbf{HRTF}^{id}_{R,\phi_n,\theta_n}(f)$) in an HRTF group (e.g., a HRTF set) may be modified to form a delay-separated HRTF (e.g., represented by the functions $\mathbf{M}^{id}_{L,\phi_n,\theta_n}(f)$, $\mathbf{M}^{id}_{R,\phi_n,\theta_n}(f)$ and $\delta^{id}_{\phi_n,\theta_n}$) according to:

1. determining a time-delay associated with each HRTF filter:

$$\tau^{id}_{ear,\phi_n,\theta_n} = \text{frequency-averaged group-delay of } \mathbf{HRTF}^{id}_{ear,\phi_n,\theta_n}(f)$$

2. determining new delay-separated filter responses by removing the respective time-delay from each HRTF response:

$$\mathbf{M}^{id}_{L,\phi_n,\theta_n}(f) = \exp\left(2i\pi f\tau^{id}_{L,\phi_n,\theta_n}\right)\mathbf{HRTF}^{id}_{L,\phi_n,\theta_n}(f)$$

$$\mathbf{M}^{id}_{R,\phi_n,\theta_n}(f) = \exp\left(2i\pi f\tau^{id}_{R,\phi_n,\theta_n}\right)\mathbf{HRTF}^{id}_{R,\phi_n,\theta_n}(f)$$

3. determining the inter-aural time delay (ITD) between Left/Right pairs:

$$\delta^{id}_{\phi_n,\theta_n} = \tau^{id}_{R,\phi_n,\theta_n} - \tau^{id}_{L,\phi_n,\theta_n}$$

[0042] Data representing an HRTF or a plurality of HRTFs (e.g. a group or set of HRTFs) may be stored or transmitted by various means, as known in the art. For example, an HRTF set may include HRTF filters corresponding to a finite number of directions of arrival. In some embodiments, various interpolation methods, as known in the art, are be used to compute HRTF filters corresponding to arbitrary directions from a finite number of DOAs .

[0043] An HRTF Library may refer to a representation of one or more HRTF sets including Left and Right ear HRTF filters along with the corresponding directions of arrival. In some embodiments, an HRTF Library includes N delay-separated HRTFs:

$$\mathbf{HRTFLib}^{id} = \{\quad \left(\phi_n, \theta_n, \mathbf{M}^{id}_{L,\phi_n,\theta_n}(f), \mathbf{M}^{id}_{R,\phi_n,\theta_n}(f), \delta^{id}_{\phi_n,\theta_n}\right): n = 1..N\} \quad (6)$$

where N is generally 8 or more, and typically is between 32 and 1024. Higher values of N will provide a more accurate representation of an HRTF Set (e.g., higher directional resolution). An HRTF Library composed from a smaller set of responses ($N < 30$, say) will provide a less accurate representation of an HRTF Set.

[0044] In some embodiments, the directions of arrival within an HRTF Library correspond to unit vectors that are uniformly spread over the surface of the unit-sphere (e.g., angular spacing between unit vectors is approximately equal). In some embodiments, the directions of arrival within an HRTF Library correspond to unit vectors that are uniformly spread over (e.g., intersecting) a section of the surface of the unit-sphere (e.g., a region of the unit-sphere surface having less surface area than the entire unit-sphere). In some embodiments, an HRTF Library includes DOAs corresponding to a fixed range of elevation angles and/or lateral angles (e.g., rotational angle relative to the median plane) on the unit-sphere.

[0045] Fig. 4 shows the process 400 by which a Left/Right pair of HRTF filters 406, corresponding to a direction of arrival (ϕ,θ) 402 are determined from an HRTF Library 401. Interpolate process 403 forms the interpolated delay-separated HRTFs 404, corresponding to a direction of arrival (ϕ,θ) 402, from HRTF Library 401. Delay-separated HRTFs 404 are processed 405 to form the Left/Right pair of HRTF filters 406.

[0046] Given a smooth function $(f(\phi,\theta)$, sampled at a number (N) of unit-vector directions ($f(\phi_n,\theta_n): n \in 1..N$), an estimate $(f'(\phi,\theta))$ of the function value at an arbitrary direction may be estimated by using a linear mixture of the sampled values:

$$f'(\phi,\theta) = \sum_{n=1}^{N} g_n\,(\phi,\theta) f(\phi_n,\theta_n) \approx f(\phi,\theta) \tag{7}$$

[0047] In some embodiments, the gain values, g_n, are chosen according to the interpolation method:

1. Define the target vector

$$V = \begin{pmatrix} \cos\phi\cos\theta \\ \sin\phi \\ \cos\phi\sin\theta \end{pmatrix}$$

2. Define the sampled vectors

$$v_n = \begin{pmatrix} \cos\phi_n\cos\theta_n \\ \sin\phi_n \\ \cos\phi_n\sin\theta_n \end{pmatrix} \text{ for } n \in 1..N$$

3. Choose the gain values g_n so that: $\sum_{n=1}^{N} g_n = 1$, and $g_n > 0$ for all $n \in 1..N$, and so that the magnitude of the error-vector ($E = V - \sum_{n=1}^{N} g_n\, v_n$) is minimised

[0048] Other interpolation methods for deriving interpolation gains $(g_n(\phi,\theta))$, for example, Vector Based Amplitude Panning and the like, may be used in accordance with some embodiments.

[0049] As illustrated in Fig. 4, HRTF Library 401 (e.g., specified according to Equation 6 above), interpolated delay-separated HRTFs 404 are estimated for an arbitrary direction of arrival (ϕ,θ), by first choosing $g_n(\phi,\theta)$ according to the interpolation method such as that defined above, and then processing, 403, according to:

$$
\begin{aligned}
\widehat{\mathbf{M}}_{L,\phi,\theta}^{id}(f) &= \textstyle\sum_{n=1}^{N} g_n\,(\phi,\theta)\mathbf{M}_{L,\phi_n,\theta_n}^{id}(f) \\
\widehat{\mathbf{M}}_{R,\phi,\theta}^{id}(f) &= \textstyle\sum_{n=1}^{N} g_n\,(\phi,\theta)\mathbf{M}_{R,\phi_n,\theta_n}^{id}(f) \\
\hat{\delta}_{\phi,\theta}^{id} &= \textstyle\sum_{n=1}^{N} g_n\,(\phi,\theta)\delta_{\phi_n,\theta_n}^{id}
\end{aligned} \tag{8}
$$

and the interpolated delay-separated HRTFs 404 are then be used to form the interpolated HRTF filters 406, according to:

$$
\begin{aligned}
\widehat{\mathbf{HRTF}}_{L,\phi,\theta}^{id}(f) &= \exp\left(-2i\pi f \max\left(0,-\delta_{\phi_n,\theta_n}^{id}\right)\right)\widehat{\mathbf{M}}_{L,\phi,\theta}^{id}(f) \\
\widehat{\mathbf{HRTF}}_{R,\phi,\theta}^{id}(f) &= \exp\left(-2i\pi f \max\left(0,\delta_{\phi_n,\theta_n}^{id}\right)\right)\widehat{\mathbf{M}}_{R,\phi,\theta}^{id}(f)
\end{aligned} \tag{9}
$$

[0050] A binaural signal, created using an HRTF set, may be intended to provide listeners with an impression of sonic objects spatially located in various locations around them. However, a specific binaural signal may provide a more realistic spatial impression for some listeners, and a less realistic spatial impression for others.

[0051] An HRTF Library that is preferred by a first listener may also be preferred by a second listener when the two listeners have similar physical and/or non-physical features, including the size of their heads, the size of their ears, and the angle or pitch of their ears.

[0052] In some embodiments, as illustrated in Fig. 5, a Starter HRTF library 501, which is preferred by listeners with a set of default parameters, associated with particular anatomical features (the Starter Features), is first obtained. Then, in processing unit 502, the Starter HRTF set 51 is modified to form a set of personalized HRTFs, pHRTFs, also referred to as a target HRTF Library 401 that is adapted for a Target subject with different anatomical features (the Target Features). The modification in processing unit 502 is based on a relationship between the default parameters and a set of personalization parameters associated with the Target subject's anatomical features 510.

[0053] The personalization parameters may be determined from one or several images of the target/user. Techniques for acquiring model parameters from features in images are discussed in co-pending application also titled, "GENERATION OF PERSONALIZED HEAD-RELATED TRANSFER FUNCTIONS (PHRTFS)", (Serial number: not yet assigned; our reference number: D22129), hereby incorporated by reference.

[0054] In other embodiments, a personalization parameter may also be determined based on a non-physical feature. For example, the age, gender, birth sex, geographic location, nationality, ethnicity or other demographic attribute of the Target subject may be used to infer (e.g., leveraging numerical and/or Machine Learning based approaches) that a physical feature is likely to have a certain size or form. As a specific example, the age of the Target subject may be used to infer that the target subject's head size differs from the default head size (e.g., the target subject's head size is smaller or larger compared to the default head size).

[0055] Fig. 6 illustrates a detailed view of a sound incident at a user's ear 4 at elevation angle θ relative to the forward-facing X-axis 101, the user possessing anatomical features compatible with the Starter HRTF Library 501 of Fig. 5. The listener's ear 4 is associated with a line A indicative of the angle of tilt of the ear 4.

[0056] Fig. 7 illustrates a similar view of a sound incident at a user's ear 4' at elevation angle θ relative to the forward-facing X-axis 101, where the user has Target anatomical features compatible with the Target HRTF Library 401 of Fig. 4. The listener's ear 4' is associated with a line A' indicative of the angle of tilt of the ear 4'. The angular difference α between the ear 4 (of Fig. 6) and the Target subject's ear 4' is herein referred to as the tilt-angle α_L (associated with the Target listener's left ear) or α_R (associated with the Target listener's right ear).

[0057] Hence, given a Starter HRTF Library:

$$\mathbf{HRTFLib}^{starter} = \{(\ \phi_n, \theta_n, \mathbf{M}_{L,\phi_n,\theta_n}^{starter}(f), \mathbf{M}_{R,\phi_n,\theta_n}^{starter}(f), \delta_{\phi_n,\theta_n}^{starter}) : n = 1..N\} \quad (10)$$

we may define a HRTF Library according to some embodiments, wherein the elevation angles in the library are adapted to compensate for the tilt-angle α_L of the Target subject's left ear, and tilt-angle α_R of the Target subject's right ear:

$$\mathbf{HRTFLib}^{target:earrot} = \{(\ \phi_n, \theta_n, \mathbf{M}_{L,\phi_n,\theta_n+\alpha_L}^{starter}(f), \mathbf{M}_{R,\phi_n,\theta_n+\alpha_R}^{starter}(f), \delta_{\phi_n,\theta_n}^{starter}) : n = 1..N\} \quad (11)$$

[0058] In an alternative preferred embodiment, when the tilt angle associated with both ears is the same ($\alpha_L = \alpha_R$), we may choose to define the Target HRTF Library according to:

$$\mathbf{HRTFLib}^{target:earrot} = \{(\ \phi_n, \theta_n - \alpha_L, \mathbf{M}_{L,\phi_n,\theta_n}^{starter}(f), \mathbf{M}_{R,\phi_n,\theta_n}^{starter}(f), \delta_{\phi_n,\theta_n}^{starter}) : n = 1..N\} \quad (12)$$

[0059] Fig. 8 illustrates a user's ear 4 with ear height h, the user possessing anatomical features compatible with the Starter HRTF Library 501 of Fig. 5. Alternative ears, 104 and 204, with ear heights h' and h'' will respond to incident acoustic waves with a frequency response that will be similar to the frequency response associated with the ear 4, but with the frequency scaled according to the ear height (h' or h'').

[0060] Similar adjustments may be determined for any other distance metric associated with two or more characteristic points of the ear. For example, just to take one example, the size, volume or surface area of the concha could be the basis of a similar adjustment,

[0061] In some embodiments, an HRTF Library adapted for a listener with anatomical features that include a scale factor β_L associated with the subject's left ear (for example, $\beta_L =$

$\frac{\text{height of Target left ear}}{\text{height of Starter left ear}}$), and a scale factor β_R associated with the subject's right ear (for example, $\beta_R = \frac{\text{height of Target right ear}}{\text{height of Starter right ear}}$), may be formed as follows:

$$\mathbf{HRTFLib}^{target:earscaled} = \{(\quad \phi_n, \theta_n, \mathbf{M}^{starter}_{L,\phi_n,\theta_n}(\beta_L f), \mathbf{M}^{starter}_{R,\phi_n,\theta_n}(\beta_R f), \delta^{starter}_{\phi_n,\theta_n}): n = 1..N\} \tag{13}$$

[0062] Fig. 9 illustrates examples of the left ear response 11 and right ear response 13 of a typical HRTF for a particular direction of arrival as per a Starter HRTF Library. Scaled left ear 12 and right ear 14 responses are shown for a Target HRTF Library associated with a Target subject with smaller ears.

[0063] In some embodiments, an HRTF Library adapted for use by a listener with anatomical features that include ear-tilt-angles α_L and α_R and ear scale factors β_L and β_R, may be formed as follows:

$$\mathbf{HRTFLib}^{target:ear} = \{(\quad \phi_n, \theta_n, \mathbf{M}^{starter}_{L,\phi_n,\theta_n+\alpha_L}(\beta_L f), \mathbf{M}^{starter}_{R,\phi_n,\theta_n+\alpha_R}(\beta_R f), \delta^{starter}_{\phi_n,\theta_n}): n = 1..N\} \tag{14}$$

[0064] It is known that the Interaural Time Difference (ITD) varies as a function of the direction of arrival. Fig. 10 shows the variation of ITD as a function of the lateral angle (ϕ) for an elevation angle $\theta = 0$. The ITD associated with a Starter HRTF Library is shown as the solid curve 15. A Target subject with a larger head will be associated with a larger ITD as shown in the dotted curve 16.

[0065] Variations in the width of the head of different listeners is associated with variations in the frequency response of the HRTFs associated with respective listeners. Hence, an HRTF Library adapted for use by a listener with anatomical features that include a scale factor β_H associated with the Target subject's head width (for example, $\beta_H = \frac{\text{width of Target head}}{\text{width of Starter head}}$), may be formed as follows:

$$\mathbf{HRTFLib}^{target:headscaled} = \{(\quad \phi_n, \theta_n, \mathbf{M}^{starter}_{L,\phi_n,\theta_n}(\beta_H f), \mathbf{M}^{starter}_{R,\phi_n,\theta_n}(\beta_H f), \beta_H \delta^{starter}_{\phi_n,\theta_n}): n = 1..N\} \tag{15}$$

[0066] Fig. 11 illustrates the processing of one of the N elements of the Starter HRTF Library, wherein the n^{th} element 801 may be processed by a direction alteration block 802, a frequency response alteration block 803 and/or an ITD alteration block 804, to produce the respective n^{th} element 805 of the Target HRTF Library.

[0067] In some embodiments, a Target HRTF Library adapted for use by a listener with anatomical features that include ear-tilt-angles α_L and α_R, ear scale factors β_L and β_R, and head scale factor β_H, may be formed as follows:

$$\begin{aligned}&\mathbf{HRTFLib}^{target} = \\ \{(\ & \phi_n, \theta_n, \\ & \mathbf{M}^{starter}_{L,\phi_n,\theta_n}(\beta_H f) \times w(f) + \mathbf{M}^{starter}_{L,\phi_n,\theta_n}(\beta_L f) \times \left(1 - w(f)\right), \\ & \mathbf{M}^{starter}_{R,\phi_n,\theta_n}(\beta_H f) \times w(f) + \mathbf{M}^{starter}_{R,\phi_n,\theta_n}(\beta_R f) \times \left(1 - w(f)\right), \\ & \beta_H \delta^{starter}_{\phi_n,\theta_n} \\ )\ & : n = 1..N\}\end{aligned} \quad (16)$$

where $w(f)$ is a cross-fade function that is equal to 1 when $f < 1\text{kHz}$ and equal to 0 when $f > 3\text{kHz}$, and is generally monotonically decreasing for frequencies between 1kHz and 3kHz.

[0068] In some embodiments, $w(f)$ is a piecewise linear function according to:

$$w(f) = \begin{cases} 1 & f < 2000 \\ 0 & f > 2500 \\ \frac{(2500 - f)}{500} & \text{otherwise} \end{cases} \quad (17)$$

[0069] In some embodiments, a Starter HRTF Library is determined by choosing an HRTF Library associated with one individual listener. In some embodiments, a Starter HRTF Library is determined by combining a collection of HRTF Libraries associated with a respective collection of listeners. In some embodiments, a Starter HRTF Library, suitable for use in forming Target HRTF Libraries associated with listeners who are members of a specific demographic group is determined by combining a collection of HRTF Libraries associated with a respective collection of listeners who are members of the specific demographic group.

[0070] In some embodiments, a number of Starter HRTF Libraries are determined as associated with a number of different demographic groups, and a Target HRTF Library 401 for a specific Target listener is formed by first selecting a Starter HRTF Library 501 that is associated with a demographic group that matches the demographic attributes of the Target listener. Subsequently, the selected Starter HRTF Library 501 is modified according to the various methods described above (e.g. equation 16) to form the Target HRTF Library 401.

[0071] In some embodiments, demographic groups are determined based on attributes including gender, birth sex, age, weight, and ethnicity. In some embodiments, demographic groups and/or related attributes are received via user input.

[0072] In some embodiments, where HRTFs are represented as time-domain impulse responses (e.g., $h(t)$), a frequency remapping (such as $M^{target}(f) = M^{starter}(\beta f)$) may be implemented by a corresponding time remapping, $h^{target}(t) = \frac{t}{\beta} h^{starter}\left(\frac{t}{\beta}\right)$.

[0073] It will be appreciated that the set of HRTFs at discrete directions (that may constitute an HRTF Library) form the basis of an HRTF function that is a function of frequency (or time) and direction. An HRTF Library may instead be defined according to spherical-harmonic based filters, according to a spherical harmonic basis set, as is known in the art. In some embodiments, a starter HRTF Library that is defined in terms of a spherical harmonic basis may be processed so as to effect a rotation around the Y axis by applying a linear mixing of the starter spherical-harmonic based filters to produce a target set of spherical-harmonic based filters.

[0074] In some embodiments, where the spherical harmonic basis is oriented so that the spherical harmonic basis functions are periodic under rotations around the Y axis, the linear mixing of the starter spherical-harmonic based filters to produce a target set of spherical-harmonic based filters may be achieved utilizing a sparse matrix.

[0075] Fig. 12 is a flow diagram illustrating a process for generating personalize HRTFs using an electronic device, in accordance with some embodiments. Process 1200 is performed at an electronic device (e.g., computing hardware as described above). Some operations in process 1200 are, optionally, combined, the orders of some operations are, optionally, changed, and some operations are, optionally, omitted.

[0076] As described below, process 1200 provides an efficient way of generating personalize HRTFs using an electronic device. The process reduces the computation requirements of performing device personalization, which for battery-operated devices, conserves power and increases the time between battery charges. Additionally, the process enables performing device personalization, such as pHRTF generation, on devices which have limited computation capabilities (e.g., a mobile device).

[0077] At step 1202, the electronic device obtains a default HRTF set related to one or several default parameters, each default parameter being associated with a specific human feature.

[0078] At step 1204, the electronic device determines at least one personalization parameter, each personalization parameter being associated with one of the specific human features of the user.

[0079] At step 1206, the electronic device modifies the default HRTF set based on a relationship between the at least one personalization parameter and corresponding default parameter(s), to determine the set of pHRTFs.

[0080] In some embodiments, the step of modifying the default HRTF set includes one of frequency remapping, frequency scaling, and angular shift.

[0081] In some embodiments, at least one of the specific human features is a physical feature. In some embodiments, at least one personalization parameter is determined based on a non-physical feature of the user. In some embodiments, at least one personalization parameter is determined based on an age of the user. In some embodiments, at least one personalization parameter is obtained from one or several images of the user.

[0082] In some embodiments, the default parameters include a default ear tilt angle, and modifying the default HRTF set includes adapting the default HRTFs to compensate for a difference between a determined ear tilt angle of the user and the default tilt angle.

[0083] In some embodiments, the default parameters include a default ear size and modifying the default HRTF set includes a frequency remapping of the default HRTFs based on a relationship between a determined ear size of the user and the default ear size. In some embodiments, the frequency remapping is based on a ratio between the determined ear size and the default ear size. In some embodiments, the default parameters include a default head size, and modifying the default HRTF set includes a frequency remapping of the default HRTFs based on a relationship between a determined head size of the user and the default head size. In some embodiments, the frequency remapping is based on a ratio between the determined head size and the default head size. In some embodiments, modifying the default HRTFs involves a cross-fade of the ear size based frequency remapping and the head size based frequency remapping.

[0084] In some embodiments, the default parameters include a default head size, and modifying the default HRTF set includes a time-delay remapping of the default HRTFs based on a relationship between a determined head size of the user and the default head size. In some embodiments, the frequency remapping is based on a ratio between the determined head size and the default head size.

[0085] In some embodiments, at least one of the default parameters is associated with a specific non-physical feature, the default parameters include a default value, and modifying the default HRTF set includes adapting the default HRTFs to compensate for a difference between a determined value corresponding to the specific non-physical feature of the user and the default value. In some embodiments, the default parameters are associated with one or more of age, gender, birth sex, geographic location, nationality, and ethnicity. In some embodiments, modifying the default HRTF set includes one of frequency remapping, frequency scaling, and angular shift. In some embodiments, the default parameters include a default age, and modifying the default HRTF set includes a frequency remapping of the default HRTFs based on a ratio between a determined age of the user and the default age.

[0086] In some embodiments, the default HRTF set is selected from a plurality of default HRTF sets, based on one or several personalization parameters associated with non-physical features of the user. In some embodiments, the personalization parameters relate to demographic attributes of the user.

[0087] Unless specifically stated otherwise, as apparent from the following discussions, it is appreciated that throughout the disclosure discussions utilizing terms such as “processing”, “computing”, “calculating”, “determining”, “analyzing” or the like, refer to the action and/or processes of a computer hardware or computing system, or similar electronic computing devices, that manipulate and/or transform data represented as physical, such as electronic, quantities into other data similarly represented as physical quantities.

[0088] It should be appreciated that in the above description of exemplary embodiments of the invention, various features of the invention are sometimes grouped together in a single embodiment, figure, or description thereof for the purpose of streamlining the disclosure and aiding in the understanding of one or more of the various inventive aspects. This method of disclosure, however, is not to be interpreted as reflecting an intention that the claimed invention requires more features than are expressly recited in each claim. Rather, as the following claims reflect, inventive aspects lie in less than all features of a single foregoing disclosed embodiment. Thus, the claims following the Detailed Description are hereby expressly incorporated into this Detailed Description, with each claim standing on its own as a separate embodiment of this invention. Furthermore, while some embodiments described herein include some but not other features included in other embodiments, combinations of features of different embodiments are meant to be within the scope of the invention, and form different embodiments, as would be understood by those skilled in the art. For example, in the following claims, any of the claimed embodiments can be used in any combination.

[0089] Furthermore, some of the embodiments are described herein as a method or combination of elements of a method that can be implemented by a processor of a computer system or by other means of carrying out the function. Thus, a processor with instructions for carrying out such a method or element of a method forms a means for carrying out the method or element of a method. Note that when the method includes several elements, e.g., several steps, no ordering of such elements is implied, unless specifically stated. Furthermore, an element described herein of an apparatus embodiment is an example of a means for carrying out the function performed by the element for the purpose of carrying out the embodiments of the invention. In the description provided herein, numerous specific details are set forth. However, it is understood that embodiments of the invention may be practiced without these specific details. In other instances, well-known methods, structures and techniques have not been shown in detail in order not to obscure an understanding of this description.

[0090] The person skilled in the art realizes that the present invention by no means is limited to the preferred embodiments described above. On the contrary, many modifications and variations are possible within the scope of the appended claims. For example, other default parameters than those mentioned above, associated with other - physical or non-physical - human features, may be utilized for the generation of personalized HRTFs.

[0091] Various aspects of the present disclosure may be appreciated from the following Enumerated Example Embodiments (EEEs):

EEE1. A method for generating a set of personalized head-related transfer functions, pHRTFs, for a user of a media playback device comprising:

– obtaining a default HRTF set related to one or several default parameters, each default parameter being associated with a specific human feature;

– determining at least one personalization parameter, each personalization parameter being associated with one of said specific human features of the user; and

– modifying said default HRTF set based on a relationship between said at least one personalization parameter and corresponding default parameter(s), to determine said set of pHRTFs.

EEE2. The method of EEE1, wherein the step of modifying the default HRTF set includes one of frequency remapping, frequency scaling, and angular shift.

EEE3. The method of EEE1 or EEE2, wherein at least one of said specific human features is a physical feature.

EEE4. The method according to EEE3, wherein at least one personalization parameter is determined based on a non-physical feature of the user.

EEE5. The method according to EEE4, wherein at least one personalization parameter is determined based on an age of the user.

EEE6. The method of EEE3, wherein at least one personalization parameter is obtained from one or several images of the user.

EEE7. The method of one of EEE3 to EEE6, wherein said default parameters include a default ear tilt angle, and wherein modifying said default HRTF set includes adapting the default HRTFs to compensate for a difference between a determined ear tilt angle of the user and said default tilt angle.

EEE8. The method of one of EEE3 to EEE6, wherein said default parameters include a default ear size, and wherein modifying said default HRTF set includes a frequency remapping of the default HRTFs based on a relationship between a determined ear size of the user and said default ear size.

EEE9. The method of EEE8, wherein the frequency remapping is based on a ratio between the determined ear size and said default ear size.

EEE10. The method of one of EEE3 to EEE6, wherein said default parameters include a default head size, and wherein modifying said default HRTF set includes a frequency remapping of the default HRTFs based on a relationship between a determined head size of the user and said default head size.

EEE11. The method of EEE10, wherein the frequency remapping is based on a ratio between the determined head size and said default head size.

EEE12. The method of claims 8 and 10, wherein modifying said default HRTFs involves a cross-fade of the ear size based frequency remapping and the head size based frequency remapping.

EEE13. The method of one of EEE3 to EEE6, wherein said default parameters include a default head size, and wherein modifying said default HRTF set includes a time-delay remapping of the default HRTFs based on a relationship between a determined head size of the user and said default head size.

EEE14. The method of EEE13, wherein the frequency remapping is based on a ratio between the determined head size and said default head size.

EEE15. The method of EEE1, wherein at least one of said default parameters is associated with a specific non-physical feature, wherein said default parameters include a default value, and wherein modifying said default HRTF set includes adapting the default HRTFs to compensate for a difference between a determined value corresponding to the specific non-physical feature of the user and said default value.

EEE16. The method of EEE15, wherein the said default parameters are associated with one or more of age, gender, birth sex, geographic location, nationality, and ethnicity.

EEE17. The method of EEE15 or EEE16, wherein the step of modifying the default HRTF set includes one of frequency remapping, frequency scaling, and angular shift.

EEE18. The method of EEE15, wherein said default parameters include a default age, and wherein modifying said default HRTF set includes a frequency remapping of the default HRTFs based on a ratio between a determined age of the user and said default age.

EEE19. The method according to any one of the preceding EEEs, wherein the default HRTF set is selected from a plurality of default HRTF sets, based on one or several personalization parameters associated with non-physical features of the user.

EEE20. The method according to EEE19, wherein the personalization parameters relate to demographic attributes of the user.

EEE21. A system for generating a set of personalized head-related transfer functions, pHRTFs, for a user of a media playback device comprising a processing unit configured to:

receive a default HRTF set related to one or several default parameters, each default parameter being associated with a specific human feature,

receive at least one personalization parameter, each personalization parameter being associated with one of said specific human features of the user, and

modify said default HRTF set based on a relationship between said at least one personalization parameter and corresponding default parameter(s), to determine said set of pHRTFs.

EEE22. A computer program product comprising computer program code portions configured to perform the method according to one of EEE1 to EEE20 when executed on a computer processor.

EEE23. A non-transitory computer-readable storage medium storing instructions which, when executed by a computing apparatus, cause the computing apparatus to perform the method according to one of EEE1 to EEE20.

CLAIMS

1. A method for generating a set of personalized head-related transfer functions, pHRTFs, for a user of a media playback device comprising:

– obtaining a default HRTF set related to one or several default parameters, each default parameter being associated with a specific human feature;

– determining at least one personalization parameter, each personalization parameter being associated with one of said specific human features of the user; and

– modifying said default HRTF set based on a relationship between said at least one personalization parameter and corresponding default parameter(s), to determine said set of pHRTFs.

2. The method of claim 1, wherein the step of modifying the default HRTF set includes one of frequency remapping, frequency scaling, and angular shift.

3. The method of claim 1 or 2, wherein at least one of said specific human features is a physical feature.

4. The method according to claim 3, wherein at least one personalization parameter is determined based on a non-physical feature of the user.

5. The method according to claim 4, wherein at least one personalization parameter is determined based on an age of the user.

6. The method of claim 3, wherein at least one personalization parameter is obtained from one or several images of the user.

7. The method of one of claims 3-6, wherein said default parameters include a default ear tilt angle, and wherein modifying said default HRTF set includes adapting the default HRTFs to compensate for a difference between a determined ear tilt angle of the user and said default tilt angle.

8. The method of one of claims 3-6, wherein said default parameters include a default ear size, and wherein modifying said default HRTF set includes a frequency remapping of the default HRTFs based on a relationship between a determined ear size of the user and said default ear size.

9. The method of claim 8, wherein the frequency remapping is based on a ratio between the determined ear size and said default ear size.

10. The method of one of claims 3-6, wherein said default parameters include a default head size, and wherein modifying said default HRTF set includes a frequency remapping of the default HRTFs based on a relationship between a determined head size of the user and said default head size.

11. The method of claim 10, wherein the frequency remapping is based on a ratio between the determined head size and said default head size.

12. The method of claims 8 and 10, wherein modifying said default HRTFs involves a cross-fade of the ear size based frequency remapping and the head size based frequency remapping.

13. The method of one of claims 3-6, wherein said default parameters include a default head size, and wherein modifying said default HRTF set includes a time-delay remapping of the default HRTFs based on a relationship between a determined head size of the user and said default head size.

14. The method of claim 13, wherein the frequency remapping is based on a ratio between the determined head size and said default head size.

15. The method of claim 1, wherein at least one of said default parameters is associated with a specific non-physical feature, wherein said default parameters include a default value, and wherein modifying said default HRTF set includes adapting the default HRTFs to compensate for a difference between a determined value corresponding to the specific non-physical feature of the user and said default value.

16. The method of claim 15, wherein the said default parameters are associated with one or more of age, gender, birth sex, geographic location, nationality, and ethnicity.

17. The method of claim 15 or 16, wherein the step of modifying the default HRTF set includes one of frequency remapping, frequency scaling, and angular shift.

18. The method of claim 15, wherein said default parameters include a default age, and wherein modifying said default HRTF set includes a frequency remapping of the default HRTFs based on a ratio between a determined age of the user and said default age.

19. The method according to any one of the preceding claims, wherein the default HRTF set is selected from a plurality of default HRTF sets, based on one or several personalization parameters associated with non-physical features of the user.

20. The method according to claim 19, wherein the personalization parameters relate to demographic attributes of the user.

21. A system for generating a set of personalized head-related transfer functions, pHRTFs, for a user of a media playback device comprising a processing unit configured to:

receive a default HRTF set related to one or several default parameters, each default parameter being associated with a specific human feature,

receive at least one personalization parameter, each personalization parameter being associated with one of said specific human features of the user, and

modify said default HRTF set based on a relationship between said at least one personalization parameter and corresponding default parameter(s), to determine said set of pHRTFs.

22. A computer program product comprising computer program code portions configured to perform the method according to one of claims 1-20 when executed on a computer processor.

23. A non-transitory computer-readable storage medium storing instructions which, when executed by a computing apparatus, cause the computing apparatus to perform the method according to one of claims 1-20.

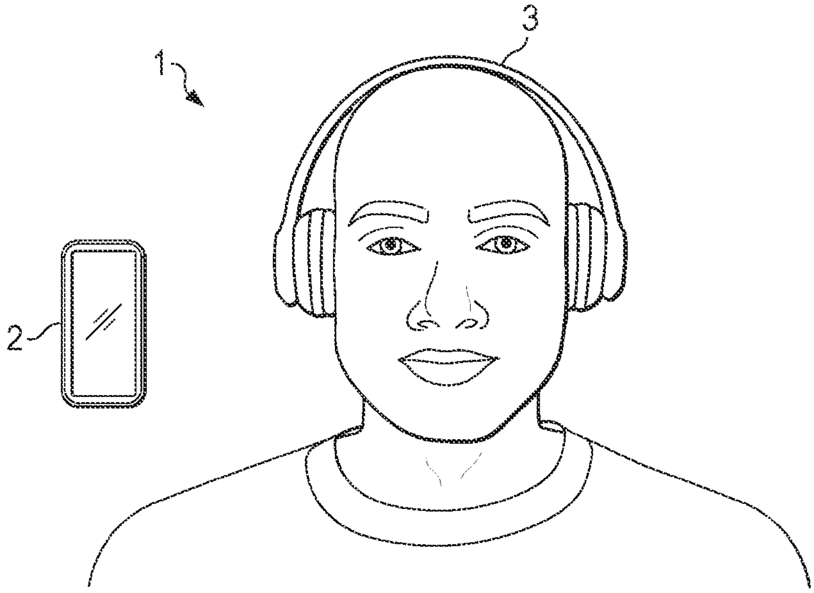


FIG. 1

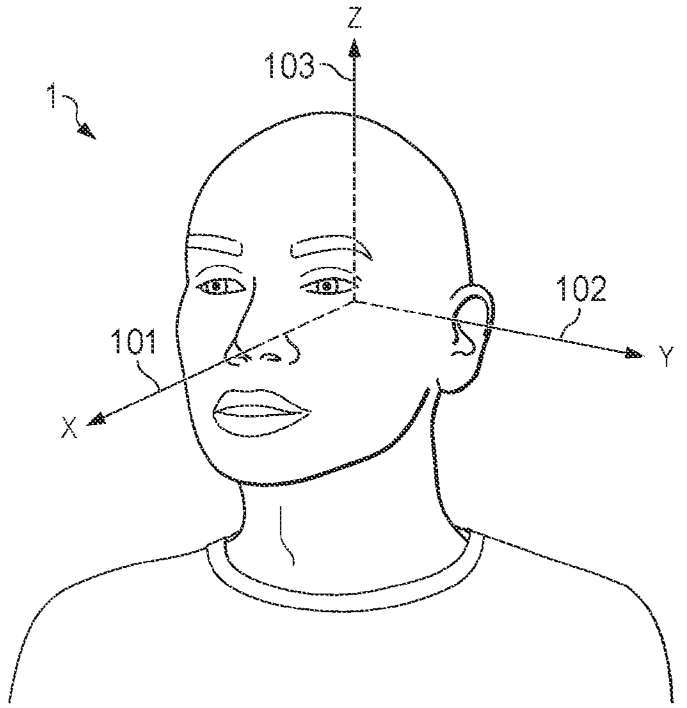


FIG. 2

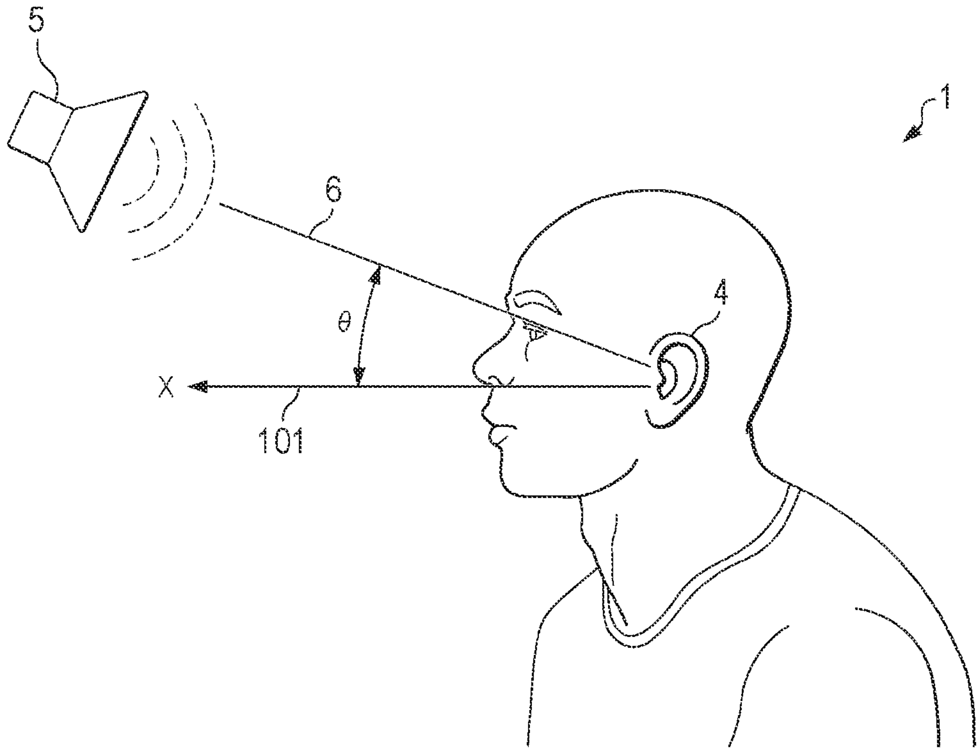
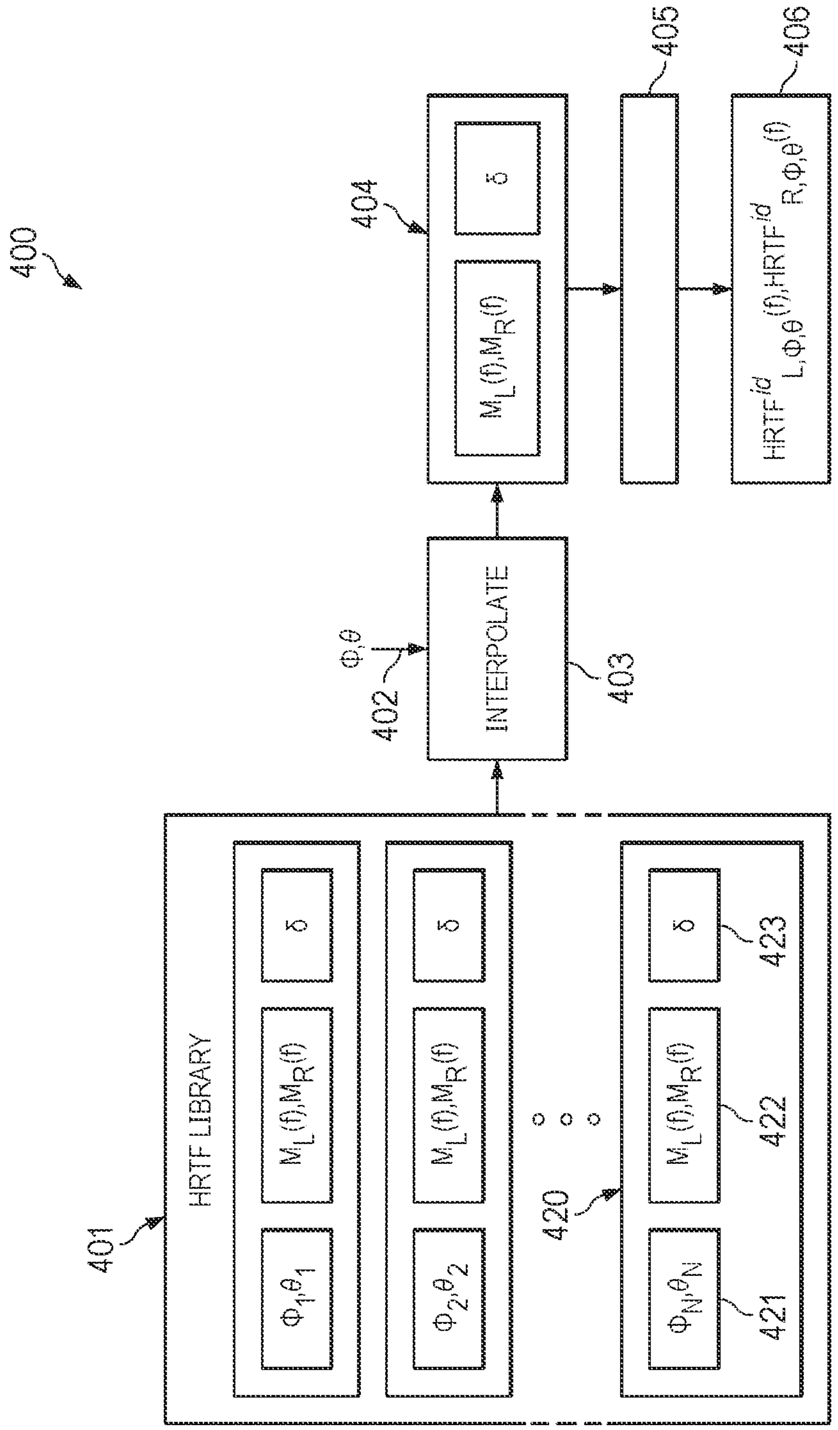


FIG. 3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HRTF LIBRARY
401
Φ_1,θ_1
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δ
Φ_2,θ_2
$M_L(f),M_R(f)$
δ
420
Φ_N,θ_N
$M_L(f),M_R(f)$
δ
421
422
423
402
Φ,θ
INTERPOLATE
403
404
$M_L(f),M_R(f)$
δ
405
406
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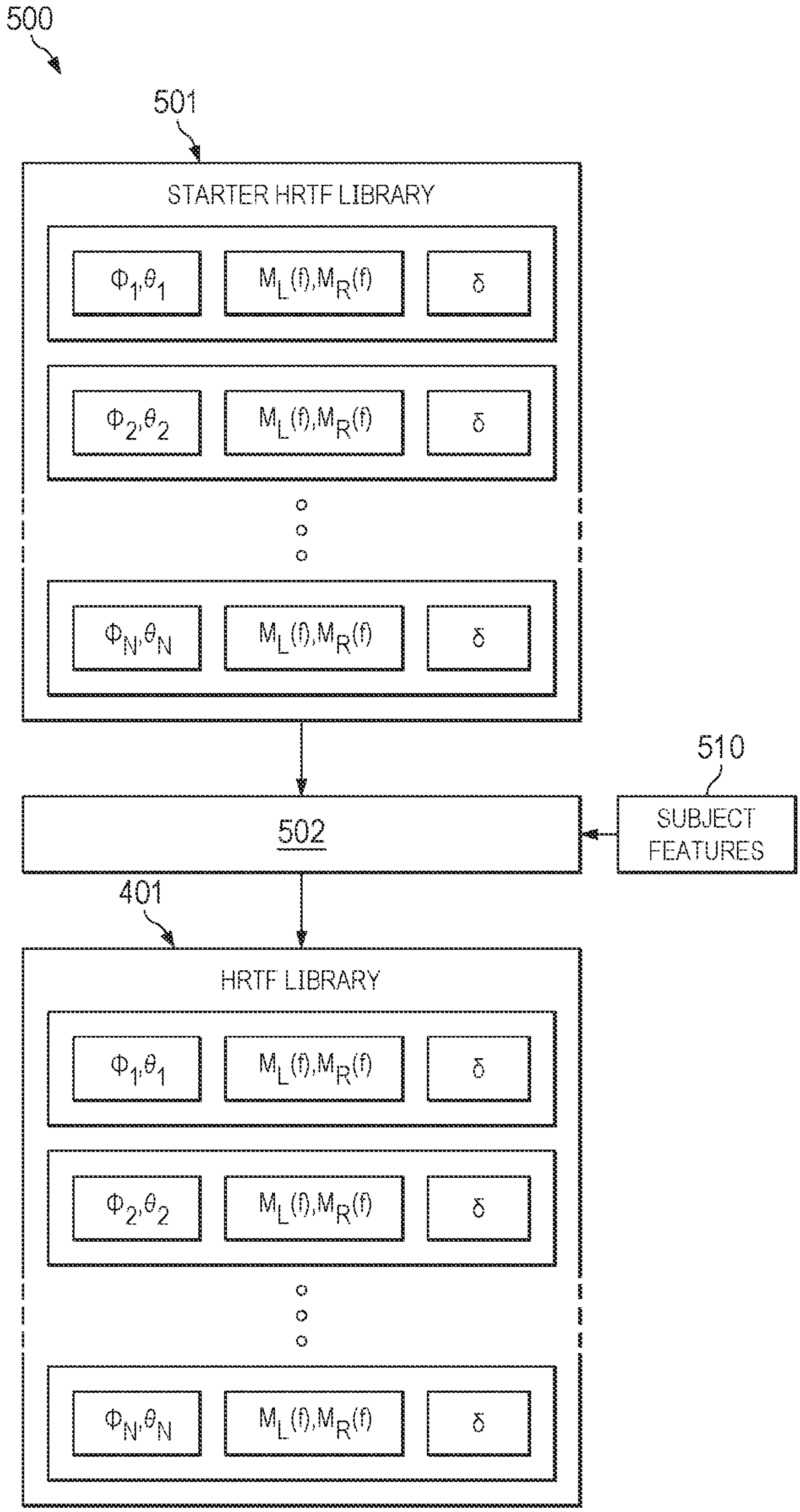
FIG. 4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501
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δ
Φ2,θ2
ML(f),MR(f)
δ
ΦN,θN
ML(f),MR(f)
δ
510
502
SUBJECT FEATURES
401
HRTF LIBRARY
Φ1,θ1
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Φ2,θ2
ML(f),MR(f)
δ
ΦN,θN
ML(f),MR(f)
δ

FIG. 5

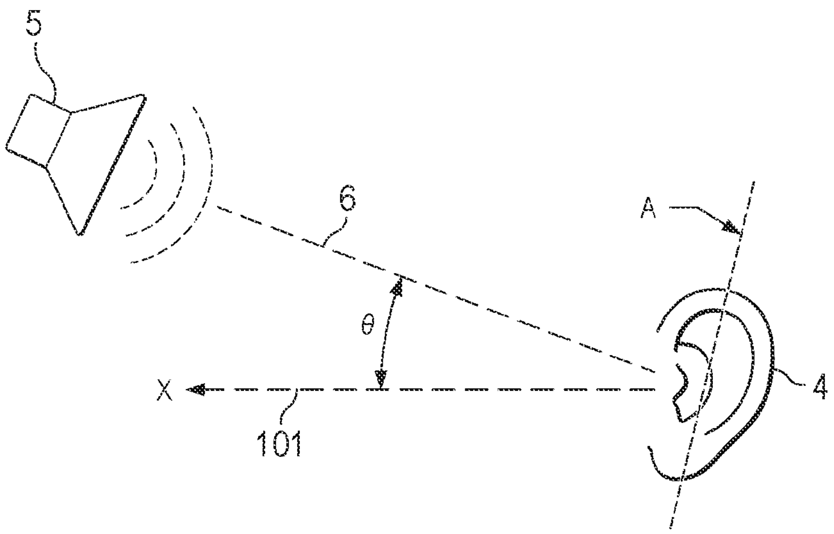


FIG. 6

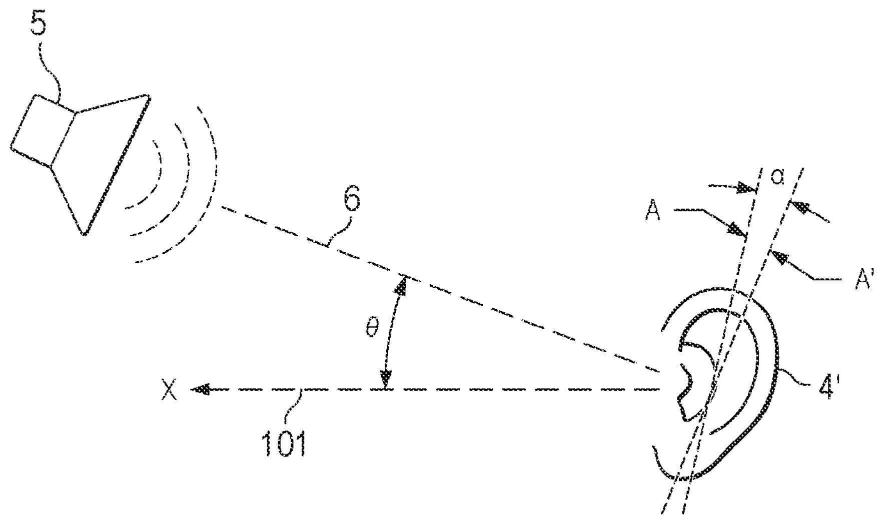


FIG. 7

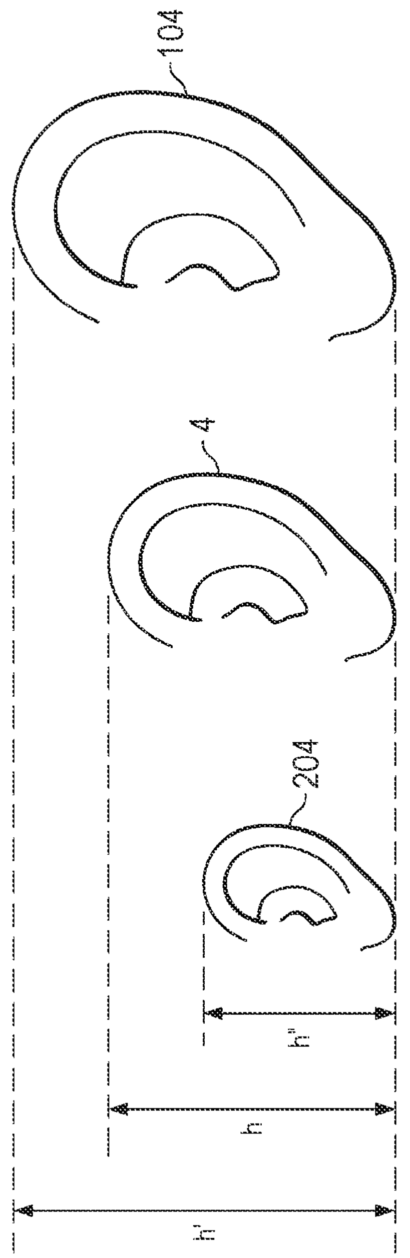


FIG. 8

FIG. 9

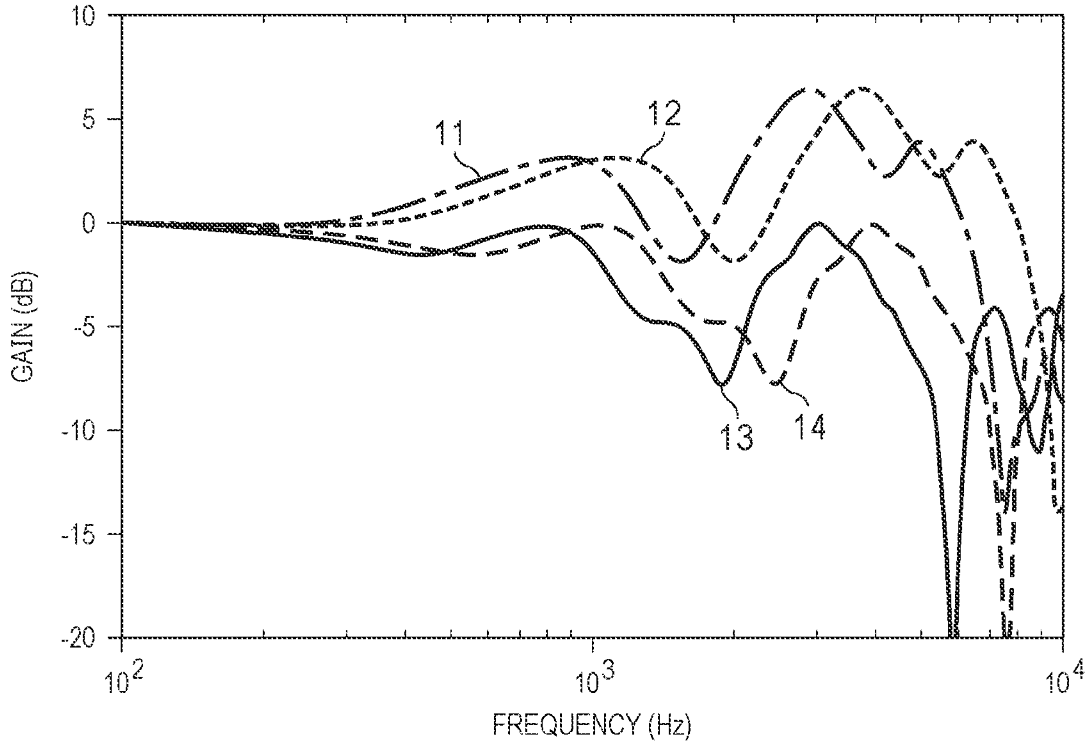
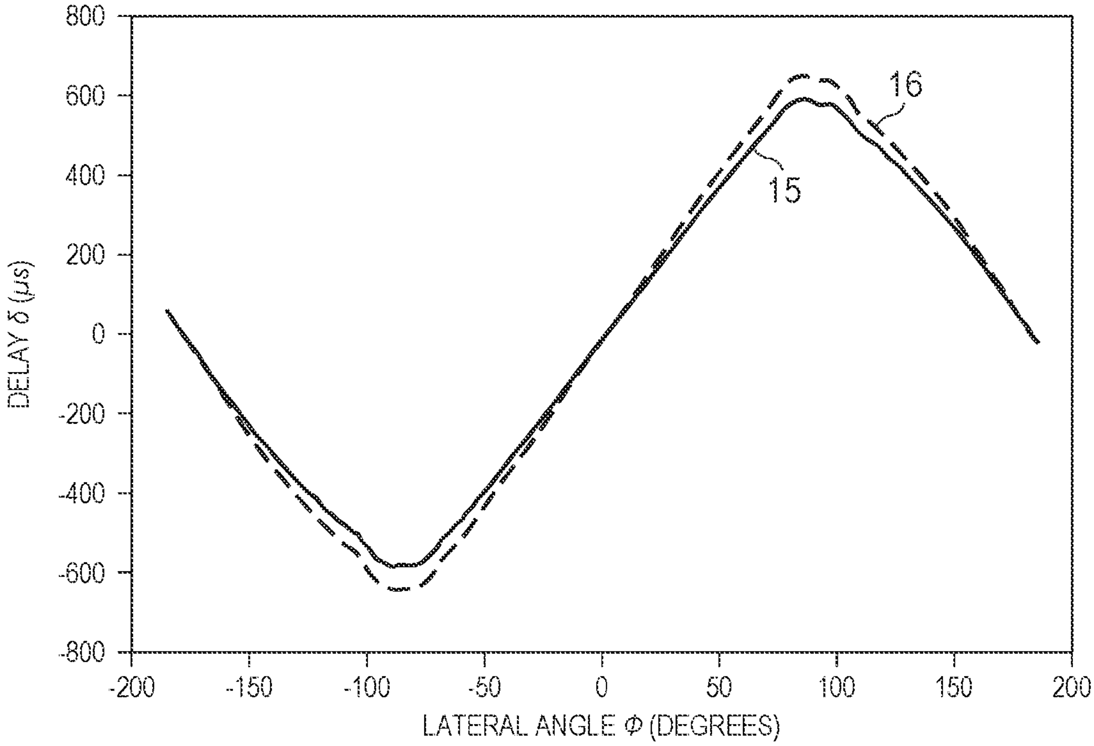


FIG. 10


800
600
400
200
0
-200
-400
-600
-800
DELAY δ (μs)
-200
-150
-100
-50
0
50
100
150
200
LATERAL ANGLE Φ (DEGREES)
16
15

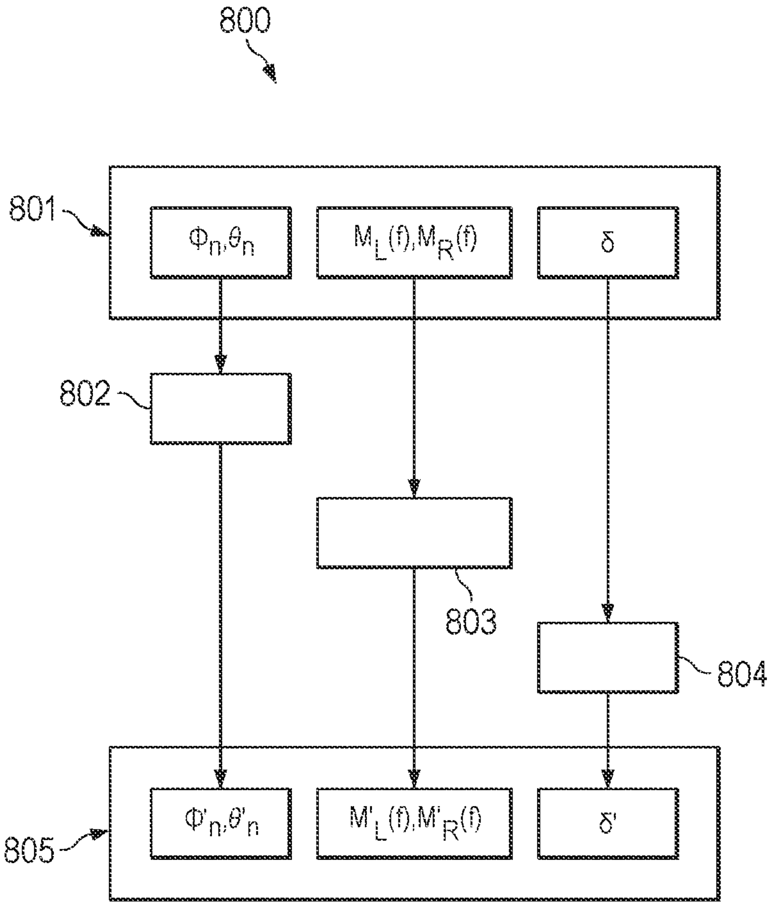

800
801
Φ_n,θ_n
$M_L(f),M_R(f)$
δ
802
803
804
805
Φ'_n,θ'_n
$M'_L(f),M'_R(f)$
δ'

FIG. 11

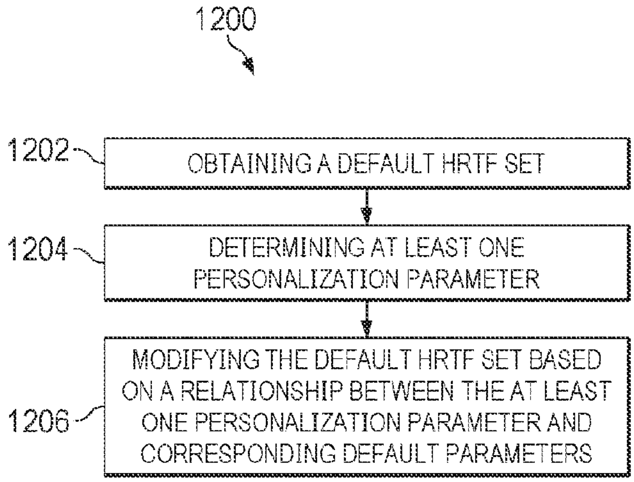

1200
1202
OBTAINING A DEFAULT HRTF SET
1204
DETERMINING AT LEAST ONE PERSONALIZATION PARAMETER
1206
MODIFYING THE DEFAULT HRTF SET BASED ON A RELATIONSHIP BETWEEN THE AT LEAST ONE PERSONALIZATION PARAMETER AND CORRESPONDING DEFAULT PARAMETERS

FIG. 12

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2024/016014

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

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)
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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	US 2020/336858 A1 (BRIMIJOIN II WILLIAM OWEN [US] ET AL) 22 October 2020 (2020-10-22) paragraphs [0003] - [0005], [0024] - [0055]	1,3-6, 8-12, 15-23 7,13,14
X Y	WO 2013/111038 A1 (KONINKL PHILIPS NV [NL]) 1 August 2013 (2013-08-01) page 14, line 7 - page 15, line 21; figure 5	1-3, 8-12,21 7

-/--

[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
13 May 2024	23/05/2024

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	Fruhmann, Markus

1

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2024/016014

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	NAVID H ZANDI ET AL: "Individualizing Head-Related Transfer Functions for Binaural Acoustic Applications", ARXIV.ORG, CORNELL UNIVERSITY LIBRARY, 201 OLIN LIBRARY CORNELL UNIVERSITY ITHACA, NY 14853, 21 March 2022 (2022-03-21), XP091181758, section 2.1.3	7
Y	US 2020/045491 A1 (ROBINSON PHILIP [US] ET AL) 6 February 2020 (2020-02-06) paragraphs [0042] - [0043]	13,14

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2024/016014

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