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(54) A hearing aid with improved localization

(57) A new hearing aid is provided with improved preservation of spatial cues of an incoming sound signal, the hearing aid comprising
a BTE hearing aid housing to be worn behind the pinna of a user,
at least one BTE sound input transducer for conversion of acoustic sound into an audio sound signal,
a processor configured to generate a hearing loss compensated output signal based on the audio sound signal,
a sound signal transmission member for transmission of a sound signal from a sound output in the BTE hearing aid housing at a first end of the sound signal transmission member to the ear canal of the user at a second end of the sound signal transmission member,
an earpiece configured to be inserted in the ear canal of the user for fastening and retaining the sound signal transmission member in its intended position in the ear canal of the user, and
an output transducer for conversion of the hearing loss compensated output signal to an auditory output signal that can be received by the human auditory system,
an ITE microphone housing accommodating at least one ITE microphone and configured to be positioned in the outer ear of the user for fastening and retaining the at least one ITE microphone in its intended position, and further comprising at least one adaptive cue filter, each of which having
an input that is provided with an output signal from a respective one of the at least one BTE sound input transducer, and
the filter coefficients of which are adapted so that the difference between an output of the at least one ITE microphone and a combined output of the at least one adaptive cue filter is minimized.

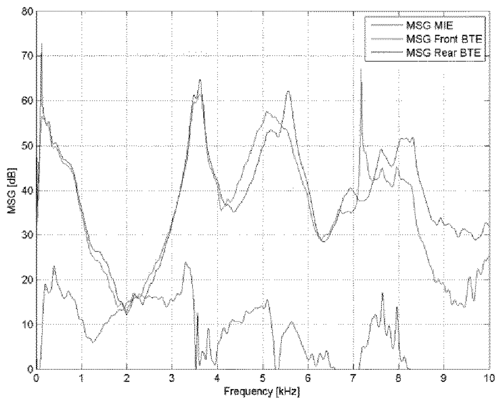

Fig. 3

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Description

FIELD OF THE INVENTION

[0001] A new Behind-The-Ear (BTE) hearing aid is provided with improved localization of sound sources with relation to the wearer of the hearing aid.

BACKGROUND

[0002] Hearing aid users have been reported to have poorer ability to localize sound sources when wearing their hearing aids than without their hearing aids. This represents a serious problem for the mild-to-moderate hearing impaired population.

[0003] Furthermore, hearing aids typically reproduce sound in such a way that the user perceives sound sources to be localized inside the head. The sound is said to be internalized rather than being externalized. A common complaint for hearing aid users when referring to the "hearing speech in noise problem" is that it is very hard to follow anything that is being said even though the signal to noise ratio (SNR) should be sufficient to provide the required speech intelligibility. A significant contributor to this fact is that the hearing aid reproduces an internalized sound field. This adds to the cognitive loading of the hearing aid user and may result in listening fatigue and ultimately that the user removes the hearing aid(s).

[0004] Thus, there is a need for a new hearing aid with improved localization of sound sources, i.e. the new hearing aid preserves information of the directions and distances of respective sound sources in the sound environment with relation to the orientation of the head of the wearer of the hearing aid.

[0005] Human beings detect and localize sound sources in three-dimensional space by means of the human binaural sound localization capability.

[0006] The input to the hearing consists of two signals, namely the sound pressures at each of the eardrums, in the following termed the binaural sound signals. Thus, if sound pressures at the eardrums that would have been generated by a given spatial sound field are accurately reproduced at the eardrums, the human auditory system will not be able to distinguish the reproduced sound from the actual sound generated by the spatial sound field itself.

[0007] It is not fully known how the human auditory system extracts information about distance and direction to a sound source, but it is known that the human auditory system uses a number of cues in this determination. Among the cues are spectral cues, reverberation cues, interaural time differences (ITD), interaural phase differences (IPD) and interaural level differences (ILD).

[0008] The transmission of a sound wave from a sound source positioned at a given direction and distance in relation to the left and right ears of the listener is described in terms of two transfer functions, one for the left ear and one for the right ear, that include any linear distortion, such as coloration, interaural time differences and interaural spectral differences. Such a set of two transfer functions, one for the left ear and one for the right ear, is called a Head-Related Transfer Function (HRTF). Each transfer function of the HRTF is defined as the ratio between a sound pressure p generated by a plane wave at a specific point in or close to the appertaining ear canal (p_L in the left ear canal and p_R in the right ear canal) in relation to a reference. The reference traditionally chosen is the sound pressure p_I that would have been generated by a plane wave at a position right in the middle of the head with the listener absent.

[0009] The HRTF contains all information relating to the sound transmission to the ears of the listener, including diffraction around the head, reflections from shoulders, reflections in the ear canal, etc., and therefore, the HRTF varies from individual to individual.

[0010] In the following, one of the transfer functions of the HRTF will also be termed the HRTF for convenience.

[0011] The hearing aid related transfer function is defined similar to a HRTF, namely as the ratio between a sound pressure p generated by the hearing aid at a specific point in the appertaining ear canal in response to a plane wave and a reference. The reference traditionally chosen is the sound pressure p_I that would have been generated by a plane wave at a position right in the middle of the head with the listener absent.

[0012] The HRTF changes with direction and distance of the sound source in relation to the ears of the listener. It is possible to measure the HRTF for any direction and distance and simulate the HRTF, e.g. electronically, e.g. by filters. If such filters are inserted in the signal path between a playback unit, such as a tape recorder, and headphones used by a listener, the listener will achieve the perception that the sounds generated by the headphones originate from a sound source positioned at the distance and in the direction as defined by the transfer functions of the filters simulating the HRTF in question, because of the true reproduction of the sound pressures in the ears.

[0013] Binaural processing by the brain, when interpreting the spatially encoded information, results in several positive effects, namely better signal-to-noise ratio (SNR); direction of arrival (DOA) estimation; depth/distance perception and synergy between the visual and auditory systems.

[0014] The complex shape of the ear is a major contributor to the individual spatial-spectral cues (ITD, ILD and spectral cues) of a listener. Devices which pick up sound behind the ear will, hence, be at a disadvantage in reproducing the HRTF since much of the spectral detail will be lost or heavily distorted.

[0015] This is exemplified in Fig. 1 where the angular frequency spectrum of an open ear, i.e. non-occluded, measurement is shown together with the corresponding measurement on the front microphone on a behind the ear device (BTE) using the same ear. The open ear spectrum is rich in detail whereas the BTE result is much more blurred and much of the spectral detail is lost.

SUMMARY

[0016] It is therefore desirable to position one or more microphones of the hearing aid at position(s) with relation to a user of the hearing aid in which spatial cues of sounds arriving at the user is preserved. It is for example advantageous to position a microphone in the outer ear of the user in front of the pinna, for example at the entrance to the ear canal; or, inside the ear canal, in order to preserve spatial cues of sounds arriving at the ear to a much larger extent than what is possible with the microphone behind the ear. A position below the triangular fossa has also proven advantageous with relation to preservation of spatial cues.

[0017] Positioning of the microphone at the entrance to the ear canal or inside the ear canal leads to the problem that the microphone is moved close to the sound emitting device of the hearing aid, whereby the risk of feedback generation is increased, which in turn limits the maximum stable gain which can be prescribed with the hearing aid.

[0018] The standard way of solving this problem is to completely seal off the ear canal using a custom mould. This, however, introduces the occlusion effect as well as comfort issues with respect to moisture and heat.

[0019] For comparison, the maximum stable gain of a BTE hearing aid with front and rear microphones positioned behind the ear, and an In-The-Ear (ITE) hearing aid with an open fitted microphone positioned in the ear canal is shown in Fig. 2. It can be seen that the ITE hearing aid has much lower maximum stable gain (MSG) than the front and rear BTE microphones for nearly all frequencies.

[0020] In the new hearing aid, output signals of an arbitrary configuration of microphones undergo signal processing in such a way that spatial cues are preserved and conveyed to the user of the hearing aid. The output signals are filtered with filters that are configured to preserve spatial cues.

[0021] The new BTE hearing aid may provide improved localization to the user by providing, in addition to conventionally positioned microphones of the BTE hearing aid, at least one ITE microphone intended to be positioned in the outer ear of the user in front of the pinna; or, inside the ear canal, when in use in order to record sound arriving at the ear of the user and containing the desired spatial information relating to localization of sound sources in the sound environment.

[0022] The signal processor of the new BTE hearing aid combines an output signal of the at least one ITE microphone in the outer ear of the user with the microphone signal(s) of the conventionally positioned microphone(s) of the BTE hearing aid in such a way that spatial cues are preserved.

[0023] Thus, a BTE hearing aid is provided, comprising
a BTE hearing aid housing to be worn behind the pinna of a user,
at least one BTE sound input transducer, such as an omni-directional microphone, a directional microphone, a transducer for an implantable hearing aid, a telecoil, a receiver of a digital audio datastream, etc., for conversion of a sound signal into respective audio sound signals ,
a processor configured to generate a hearing loss compensated output signal based on the audio sound signals ,
a sound signal transmission member for transmission of a signal representing the hearing loss compensated output signal from a sound output of the BTE hearing aid housing at a first end of the sound signal transmission member to the ear canal of the user at a second end of the sound signal transmission member,
an earpiece configured to be inserted in the ear canal of the user for fastening and retaining the sound signal transmission member in its intended position in the ear canal of the user, and
an output transducer for conversion of the hearing loss compensated output signal to an auditory output signal that can be received by the human auditory system,
an ITE microphone housing accommodating at least one ITE microphone and configured to be positioned in the outer ear of the user for fastening and retaining the at least one ITE microphone in its intended position, and wherein
the processor is further configured for processing the output signals of the at least one ITE microphone and the at least one BTE sound input transducer in such a way that the hearing loss compensated output signal substantially preserves spatial cues, such as the spatial cues recorded by the at least one ITE microphone, or recorded by the combination of the at least one ITE microphone and the at least one BTE sound input transducer.

[0024] The BTE hearing aid may be a multi-channel hearing aid in which signals to be processed are divided into a plurality of frequency channels, and wherein signals are processed individually in each of the frequency channels.

[0025] The processor may be configured for processing the output signals of the at least one ITE microphone and the at least one BTE sound input transducer in such a way that the hearing loss compensated output signal substantially preserves spatial cues in a selected frequency band.

[0026] The selected frequency band may comprise one or more of the frequency channels, or all of the frequency channels. The selected frequency band may be fragmented, i.e. the selected frequency band need not comprise consecutive frequency channels.

[0027] The plurality of frequency channels may include warped frequency channels, for example all of the frequency channels may be warped frequency channels.

[0028] Outside the selected frequency band, the at least one ITE microphone may be connected conventionally as an input source to the signal processor of the hearing aid and may cooperate with the signal processor of the hearing aid in a well-known way.

[0029] In this way, the at least one ITE microphone supplies the input to the hearing aid at frequencies where the hearing aid is capable of supplying the desired gain with this configuration. In the selected frequency band, wherein the hearing aid cannot supply the desired gain with this configuration, the microphones of BTE hearing aid housing are included in the signal processing as disclosed above. In this way, the gain can be increased while simultaneously maintain the spatial information about the sound environment provided by the at least one ITE microphone.

[0030] The hearing aid may for example comprise a first filter connected between the processor input and the at least one ITE microphone, and a second complementary filter connected between the processor input and a combined output of the at least one BTE sound input transducer, the filters passing and blocking frequencies in complementary frequency bands so that one of the at least one ITE microphone and the combined output of at least one BTE sound input transducer constitutes the main part of the input signal supplied to the processor input in one frequency band, and the other one of the at least one ITE microphone and the combined output of at least one BTE sound input transducer constitutes the main part of the input signal supplied to the processor input in the complementary frequency band.

[0031] In this way, the at least one ITE microphone may be used as the sole input source to the processor in a frequency band wherein the required gain for hearing loss compensation can be applied to the output signal of the at least one ITE microphone. Outside this frequency band, the combined output signal of the at least one BTE sound input transducer is applied to the signal processor for provision of the required gain.

[0032] The combined output signal of the at least one BTE sound input transducer may be subject to adaptive filtering in the ways described elsewhere in the present description. The combination of the signals could e.g. be based on different types of band pass filtering.

[0033] Throughout the present disclosure, the "output signals of the at least one ITE microphone" may be used to identify any analogue or digital signal forming part of the signal path from the output of the at least one ITE microphone to an input of the processor, including pre-processed output signals of the at least one ITE microphone.

[0034] Likewise, the "output signals of the at least one BTE sound input transducer" may be used to identify any analogue or digital signal forming part of the signal path from the at least one BTE sound input transducer to an input of the processor, including pre-processed output signals of the at least one BTE sound input transducer.

[0035] In use, the at least one ITE microphone is positioned so that the output signal of the at least one ITE microphone generated in response to the incoming sound has a transfer function that constitutes a good approximation to the HRTFs of the user. The signal processor conveys the directional information contained in the output signal of the at least one ITE microphone to the resulting hearing loss compensated output signal of the processor so that the hearing loss compensated output signal of the processor also attains a transfer function that constitutes a good approximation to the HRTFs of the user whereby improved localization is provided to the user.

[0036] BTE (behind-the-ear) hearings aids are well-known in the art. A BTE hearing aid has a BTE housing that is shaped to be worn behind the pinna of the user. The BTE housing accommodates components for hearing loss compensation. A sound signal transmission member, i.e. a sound tube or an electrical conductor, transmits a signal representing the hearing loss compensated sound from the BTE housing into the ear canal of the user.

[0037] In order to position the sound signal transmission member securely and comfortably at the entrance to the ear canal of the user, an earpiece, shell, or earmould may be provided for insertion into the ear canal of the user constituting an open solution. In an open solution, the earpiece, shell, or earmould does not obstruct the ear canal when it is positioned in its intended operational position in the ear canal. Rather, there will be a passageway through the earpiece, shell, or earmould or, between a part of the ear canal wall and a part of the earpiece, shell, or earmould, so that sound waves may escape from behind the earpiece, shell, or earmould between the ear drum and the earpiece, shell, or earmould through the passageway to the surroundings of the user. In this way, the occlusion effect is substantially eliminated.

[0038] Typically, the earpiece, shell, or earmould is individually custom manufactured or manufactured in a number of standard sizes to fit the user's ear to sufficiently secure the sound signal transmission member in its intended position in the ear canal and prevent the earpiece from falling out of the ear, e.g., when the user moves the jaw.

[0039] The output transducer may be a receiver positioned in the BTE hearing aid housing. In this event, the sound signal transmission member comprises a sound tube for propagation of acoustic sound signals from the receiver positioned in the BTE hearing aid housing and through the sound tube to an earpiece positioned and retained in the ear canal of the user and having an output port for transmission of the acoustic sound signal to the eardrum in the ear canal.

[0040] The output transducer may be a receiver positioned in the earpiece. In this event, the sound signal transmission member comprises electrical conductors for propagation of audio sound signals from the output of a signal processor in the BTE hearing aid housing through the conductors to a receiver positioned in the earpiece for emission of sound through an output port of the earpiece.

[0041] The ITE microphone housing accommodating at least one ITE microphone may be combined with, or be constituted by, the earpiece so that the at least one microphone is positioned proximate the entrance to the ear canal when the earpiece is fastened in its intended position in the ear canal.

[0042] The ITE microphone housing may be connected to the earpiece with an arm, possibly a flexible arm that is intended to be positioned inside the pinna, e.g. around the circumference of the conchae abutting the antihelix and at least partly covered by the antihelix for retaining its position inside the outer ear of the user. The arm may be pre-formed during manufacture, preferably into an arched shape with a curvature slightly larger than the curvature of the antihelix, for easy fitting of the arm into its intended position in the pinna. In one example, the arm has a length and a shape that facilitate positioning of the at least one ITE microphone in an operating position immediately below the triangular fossa.

[0043] The signal processor may be accommodated in the BTE hearing aid housing, or in the ear piece, or part of the signal processor may be accommodated in the BTE hearing aid housing and part of the signal processor may be accommodated in the ear piece. There is a one-way or two-way communication link between circuitry of the BTE hearing aid housing and circuitry of the earpiece. The link may be wired or wireless.

[0044] Likewise, there is a one-way or two-way communication link between circuitry of the BTE hearing aid housing and the at least one ITE microphone. The link may be wired or wireless.

[0045] The signal processor operates to perform hearing loss compensation while maintaining spatial information of the sound environment for optimum spatial performance of the hearing aid and while at the same time providing as large maximum stable gain as possible.

[0046] The output signal of the at least one ITE microphone of the earpiece may be a combination of several pre-processed ITE microphone signals or the output signal of a single ITE microphone of the at least one ITE microphone. The short time spectrum for a given time instance of the output signal of the at least one ITE microphone of the earpiece is denoted $S^{IEC}(f,t)$ (IEC = In the Ear Component).

[0047] One or more output signals of the at least one BTE sound input transducers are provided. The spectra of these signals are denoted S_1^{BTEC} (*f,t*)t), and S_2^{BTEC} etc (BTEC = Behind The Ear Component). The output signals may be pre-processed. Pre-processing may include, without excluding any form of processing; adaptive and/or static feedback suppression, adaptive or fixed beamforming and pre-filtering.

[0048] Adaptive filters may be configured to adaptively filter the electronic output signals of the at least one BTE sound input transducer so that they correspond to the output signal of the at least one ITE microphone as closely as possible. The adaptive filters G_1, G_2, ... , G_n have the respective transfer functions: $G_1(f,t)$, $G_2(f,t)$, ..., $G_n(f,t)$.

[0049] The at least one ITE microphone operates as monitor microphone(s) for generation of an electronic sound signal with the desired spatial information of the current sound environment.

[0050] Each output signal of the at least one BTE sound input transducer is filtered with a respective adaptive filter, the filter coefficients of which are adapted to provide a combined output signal of the adaptive filter(s) that resembles the electronic sound signal provided by the at least one ITE microphone as closely as possible.

[0051] The filter coefficients are adapted to obtain an exact or approximate solution to the following minimization problem:

$$\min_{G_1(f,t)\ldots G_n(f,t)} \left\| S^{IEC}(f,t) - G_1(f,t)\, S_1^{BTEC}(f,t) - \ldots - G_{\boldsymbol{n}}(f,t) S_{\boldsymbol{n}}^{BTEC}(f,t) \right\|^p \qquad \textbf{Eqn. 1}$$

wherein p is the norm. Preferably p = 2.

[0052] The algorithm controlling the adaption could (without being restricted to) e.g. be based on least mean square (LMS) or recursive least squares (RLS), possibly normalized, optimization methods in which p = 2.

[0053] Various weights may be incorporated into the minimization problems above so that the solution is optimized as specified by the values of the weights. For example, frequency weights W(f) may optimize the solution in certain one or more frequency ranges. Thus, the minimization problem may be modified into:

$$\min_{G_1(f,t)\ldots G_n(f,t)} \left\| \boldsymbol{W(f)}(S^{IEC}(f,t) - G_1(f,t)\, S_1^{BTEC}(f,t) - \ldots - G_{\boldsymbol{n}}(f,t) S_{\boldsymbol{n}}^{BTEC}(f,t)) \right\|^p$$

[0054] Further, in one or more selected frequency ranges, only magnitude of the transfer functions may be taken into account during minimization while phase is disregarded, i.e. in the one or more selected frequency range, the transfer function is substituted by its absolute value.

[0055] Subsequent to the adaptive filtering, the combined output signal of the adaptive filter(s) is passed on for further hearing loss compensation processing, e.g. with a compressor. In this way, only signals from the at least one BTE sound input transducer is possibly amplified as a result of hearing loss compensation while the electronic output signal of the alt least one ITE microphone is not affected by the hearing loss compensation processing, whereby possible feedback from the output transducer to the at least one ITE microphone is minimized and a large maximum stable gain can be provided.

[0056] For example, in a hearing aid with one ITE microphone, and two BTE microphones constituting the at least one BTE sound input transducer, and in the event that the incident sound field consist of sound emitted by a single speaker, the emitted sound having the short time spectrum X(f,t); then, under the assumption that no pre-processing is performed with relation to the ITE microphone signal and that the ITE microphone reproduces the actual HRTF perfectly then the following signals are provided:

$$\boldsymbol{S^{IEC}(f,t) = HRTF(f)X(f,t)} \qquad \textbf{Eqn. 2}$$

$$\boldsymbol{S_{1,2}^{BTEC}(f,t) = H_{1,2}(f)X(f,t)} \qquad \textbf{Eqn. 3}$$

where $H_{1,2}$ (f) are the hearing aid related transfer functions of the two BTE microphones.

[0057] After sufficient adaptation, the hearing aid impulse response convolved with the resulting adapted filters and summed will be equal the actual HRTF so that

$$\boldsymbol{\lim_{t\to\infty} G_1(f,t)\,H_1(f) + G_2(f,t)H_2(f) = HRTF(f)} \qquad \textbf{Eqn. 4}$$

[0058] If the speaker moves and thereby changes the HRTF, the adaptive filters, i.e. the algorithm adjusting the filter coefficients, adapt towards the new minimum of Eqn. 1. The time constants of the adaptation are set to appropriately respond to changes of the current sound environment.

[0059] As used herein, the terms "processor", "signal processor", "controller", "system", etc., are intended to refer to CPU-related entities, either hardware, a combination of hardware and software, software, or software in execution.

[0060] For example, a "processor", "signal processor", "controller", "system", etc., may be, but is not limited to being, a process running on a processor, a processor, an object, an executable file, a thread of execution, and/or a program.

[0061] By way of illustration, the terms "processor", "signal processor", "controller", "system", etc., designate both an application running on a processor and a hardware processor. One or more "processors", "signal processors", "controllers", "systems" and the like, or any combination hereof, may reside within a process and/or thread of execution, and one or more "processors", "signal processors", "controllers", "systems", etc., or any combination hereof, may be localized on one hardware processor, possibly in combination with other hardware circuitry, and/or distributed between two or more hardware processors, possibly in combination with other hardware circuitry.

BRIEF DESCRIPTION OF THE DRAWINGS

[0062] In the following, preferred embodiments of the invention is explained in more detail with reference to the drawing, wherein

Fig. 1 shows a plot of the angular frequency spectrum of an open ear,

Fig. 2 shows a plot of the angular frequency spectrum of a BTE front microphone worn at the same ear,

Fig. 3 shows plots of maximum stable gain of a BTE front and rear microphones and an open fitted ITE microphone positioned in the ear canal,

Fig. 4 schematically illustrates an exemplary new BTE hearing aid,

Fig. 5 schematically illustrates another exemplary new BTE hearing aid,

Fig. 6 shows in perspective a new BTE hearing aid with an ITE-microphone in the outer ear of a user,

Fig. 7 shows a schematic block diagram of an exemplary new BTE hearing aid with adaptive filters,

Fig. 8 , shows a schematic block diagram of an exemplary new BTE hearing aid with an arbitrary number of microphones, and

Fig. 9 shows a schematic block diagram of an exemplary new multi-channel BTE hearing aid.

DETAILED DESCRIPTION OF THE DRAWINGS

[0063] The present invention will now be described more fully hereinafter with reference to the accompanying drawings, in which exemplary embodiments of the invention are shown. The invention may, however, be embodied in different forms and should not be construed as limited to the embodiments set forth herein. Rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. Like reference numerals refer to like elements throughout. Like elements will, thus, not be described in detail with respect to the description of each figure.

[0064] Fig. 4 schematically illustrates a BTE hearing aid 10 comprising a BTE hearing aid housing 12 (not shown - outer walls have been removed to make internal parts visible) to be worn behind the pinna 100 of a user. The BTE housing 12 accommodates at least one BTE sound input transducer 14, 16 with a front microphone 14 and a rear microphone 16 for conversion of a sound signal into a microphone audio sound signal, optional pre-filters (not shown) for filtering the respective microphone audio sound signals, A/D converters (not shown) for conversion of the respective microphone audio sound signals into respective digital microphone audio sound signals that are input to a processor 18 configured to generate a hearing loss compensated output signal based on the input digital audio sound signals.

[0065] The hearing loss compensated output signal is transmitted through electrical wires contained in a sound signal transmission member 20 to a receiver 22 for conversion of the hearing loss compensated output signal to an acoustic output signal for transmission towards the eardrum of a user and contained in an earpiece 24 that is shaped (not shown) to be comfortably positioned in the ear canal of a user for fastening and retaining the sound signal transmission member in its intended position in the ear canal of the user as is well-known in the art of BTE hearing aids.

[0066] The earpiece 24 also holds one ITE microphone 26 that is positioned at the entrance to the ear canal when the earpiece is positioned in its intended position in the ear canal of the user. The ITE microphone 26 is connected to an A/D converter (not shown) and optional to a pre-filter (not shown) in the BTE housing 12, with electrical wires (not visible) contained in the sound transmission member 20.

[0067] The BTE hearing aid 10 is powered by battery 28.

[0068] Various possible functions of the processor 18 are disclosed above and some of these in more detail below.

[0069] Fig. 5 schematically illustrates another BTE hearing aid 10 similar to the hearing aid shown in Fig. 1, except for the difference that in Fig. 5, the receiver 22 is positioned in the hearing aid housing 12 and not in the earpiece 24, so that acoustic sound output by the receiver 22 is transmitted through the sound tube 20 and towards the eardrum of the user when the earpiece 24 is positioned in its intended position in the ear canal of the user.

[0070] The positioning of the ITE microphone 26 proximate the entrance to the ear canal of the user when the BTE hearing aids 10 of Figs. 4 and 5 are used is believed to lead to a good reproduction of the HRTFs of the user.

[0071] Fig. 6 shows a BTE hearing aid 10 in its operating position with the BTE housing 12 behind the ear, i.e. behind the pinna 100, of the user. The illustrated BTE hearing aid 10 is similar to the hearing aids shown in Figs. 4 and 5 except for the fact that the ITE microphone 26 is positioned in the outer ear of the user outside the ear canal at the free end of an arm 30. The arm 30 is flexible and the arm 30 is intended to be positioned inside the pinna 100 , e.g. around the circumference of the conchae 102 behind the tragus 104 and antitragus 106 and abutting the antihelix 108 and at least partly covered by the antihelix for retaining its position inside the outer ear of the user. The arm may be pre-formed during manufacture, preferably into an arched shape with a curvature slightly larger than the curvature of the antihelix 104, for easy fitting of the arm 30 into its intended position in the pinna. The arm 30 contains electrical wires (not visible) for interconnection of the ITE microphone 26 with other parts of the BTE hearing aid circuitry.

[0072] In one example, the arm 30 has a length and a shape that facilitate positioning of the ITE microphone 26 in an operating position below the triangular fossa.

[0073] Fig. 7 is a block diagram illustrating one example of signal processing in the new BTE hearing aid 10. The BTE hearing aid 10 has a front microphone 14 and a rear microphone 16 for conversion of a sound signals arriving at the microphones 14, 16 into microphone audio sound signals. Further, an ITE microphone 26 resides in an earpiece to be positioned in the outer ear of the user. The microphone audio sound signals are digitized and pre-processed, such as pre-filtered, in respective pre-processors 32, 34, 36. The microphone audio sound signals 38, 40 of the front and rear microphones 14, 16 are filtered in adaptive filter 42, 44, and the adaptively filtered signals are added to each other in adder 46 and input to a processor 18 for hearing loss compensation. The hearing loss compensated signal is output to a receiver 22 that converts the signal to an acoustic signal for transmission towards the ear drum of the user.

[0074] Adaptation of the filter coefficients of adaptive filters 42, 44 are controlled by adaptive controller 48 that controls the adaptation of the filter coefficients to minimize the difference 50 between the output of adder 46 and the ITE microphone audio sound signal 52 provided by subtractor 54. In this way, the input signal 56 to the processor 18 models the microphone audio sound signal 52 of the ITE microphone 26, and thus also substantially models the HRTFs of the user.

[0075] The pre-processed output signal 52 of the ITE microphone 26 of the earpiece has a short time spectrum denoted $S^{IEC}(,t)$ (IEC = In the Ear Component).

[0076] The spectra of the pre-processed audio sound signals 38, 40 of the front and rear microphones 14, 16 are denoted $S_1^{BTEC}(f,t)$, and $S_2^{BTEC}(f,t)$(BTEC = Behind The Ear Component). Pre-processing may include, without excluding any form of processing; adaptive and/or static feedback suppression, adaptive or fixed beamforming and pre-filtering.

[0077] The adaptive controller 48 is configured to control the filter coefficients of adaptive filters 42, 44 so that their summed output 56 corresponds to the pre-processed output signal 52 of the ITE microphone 26 as closely as possible.

[0078] The adaptive filters 42, 44 have the respective transfer functions: $G_1(f,t)$, and $G_2(f,t)$.

[0079] The ITE microphone 26 operates as monitor microphone for generation of an electronic sound signal 56 with the desired spatial information of the current sound environment.

[0080] Thus, the filter coefficients are adapted to obtain an exact or approximate solution to the following minimization problem:

$$\min_{G_1(f,t),G_2(f,t)} \left\| S^{IEC}(f,t) - G_1(f,t)\, S_1^{BTEC}(f,t) - G_2(f,t) S_2^{BTEC}(f,t) \right\|^p \qquad \text{Eqn. 1}$$

[0081] P is the norm-factor, preferably p = 2.

[0082] The algorithm controlling the adaption could (without being restricted to) e.g. be based on least mean square (LMS) or recursive least squares (RLS), possibly normalized, optimization methods. in which p = 2.

[0083] Various weights may be incorporated into the minimization problems above so that the solution is optimized as specified by the values of the weights. For example, frequency weights W(f) may optimize the solution in certain one or more frequency ranges. Thus, the minimization problem may be modified into:

$$\min_{G_1(f,t)\dots G_n(f,t)} \left\| \boldsymbol{W}(\boldsymbol{f})(S^{IEC}(f,t) - G_1(f,t)\, S_1^{BTEC}(f,t) - \dots - G_{\boldsymbol{n}}(f,t) S_{\boldsymbol{n}}^{BTEC}(f,t)) \right\|^p$$

[0084] Subsequent to the adaptive filtering, the combined output signal of the adaptive filter(s) is passed on for further hearing loss compensation processing, e.g. with a compressor. In this way, only signals from the front and rear microphones 14, 16 are possibly amplified as a result of hearing loss compensation while the electronic output signal of the ITE microphone 26 is not affected by the hearing loss compensation processing, whereby possible feedback from the output transducer 22 to the ITE microphone 26 is minimized and a large maximum stable gain can be provided.

[0085] For example, in the event that the incident sound field consist of sound emitted by a single speaker, the emitted sound having the short time spectrum X(f,t); then, under the assumption that no pre-processing is performed with relation to the ITE microphone signal 52 and that the ITE microphone 26 reproduces the actual HRTF perfectly then the following signals are provided:

$$\boldsymbol{S^{IEC}(f,t) = HRTF(f)X(f,t)} \qquad \text{Eqn. 2}$$

$$\boldsymbol{S_{1,2}^{BTEC}(f,t) = H_{1,2}(f)X(f,t)} \qquad \text{Eqn. 3}$$

where $H_{1,2}$ (f) are the hearing aid related transfer functions of the two BTE microphones 14, 16.

[0086] After sufficient adaptation, the hearing aid impulse response convolved with the resulting adapted filters and summed will be equal the actual HRTF so that

$$\lim_{t\to\infty} G_1(f,t)\,H_1(f) + G_2(f,t)H_2(f) = HRTF(f) \qquad \text{Eqn. 4}$$

[0087] If the speaker moves and thereby changes the HRTF, the adaptive filters 42, 44, i.e. the controller 48 adjusting the filter coefficients, adapt towards the new minimum of Eqn. 1. The time constants of the adaptation are set to appropriately respond to changes of the current sound environment.

[0088] The new BTE hearing aid circuitry shown in Fig. 7 may operate in the entire frequency range of the BTE hearing aid 10.

[0089] The BTE hearing aid 10 shown in Fig. 7 may be a multi-channel hearing aid in which microphone audio sound signals 38, 40, 52 to be processed are divided into a plurality of frequency channels, and wherein signals are processed individually in each of the frequency channels.

[0090] For a multi-channel BTE hearing aid 10, Fig. 7 may illustrate the circuitry and signal processing in a single frequency channel. The circuitry and signal processing may be duplicated in a plurality of the frequency channels, e.g. in all of the frequency channels.

[0091] For example, the signal processing illustrated in Fig. 7 may be performed in a selected frequency band, e.g. selected during fitting of the hearing aid to a specific user at a dispenser's office.

[0092] The selected frequency band may comprise one or more of the frequency channels, or all of the frequency channels. The selected frequency band may be fragmented, i.e. the selected frequency band need not comprise consecutive frequency channels.

[0093] The plurality of frequency channels may include warped frequency channels, for example all of the frequency channels may be warped frequency channels.

[0094] Outside the selected frequency band, the at least one ITE microphone may be connected conventionally as an input source to the signal processor of the hearing aid and may cooperate with the signal processor of the hearing aid in a well-known way.

[0095] In this way, the at least one ITE microphone supplies the input to the hearing aid at frequencies where the hearing aid is capable of supplying the desired gain with this configuration. In the selected frequency band, wherein the hearing aid cannot supply the desired gain with this configuration, the microphones of BTE hearing aid housing are included in the signal processing as disclosed above. In this way, the gain can be increased while simultaneously maintain the spatial information about the sound environment provided by the at least one ITE microphone.

[0096] Fig. 8 is a block diagram illustrating a new BTE hearing aid 10 similar to the hearing aid 10 shown in Fig. 7 and operating in a way similar to the hearing aid 10 shown in Fig. 7, except for the fact that the circuit has been generalized to include an arbitrary number N of ITE microphones 26-1, 26-2, ... , 26-N, and an arbitrary number M of BTE microphones 14-1, 14-2, ... , 14-M. In Fig. 7, N=1 and M = 2. In Fig. 8, N and M can be any non-negative integer.

[0097] The output signals from the N ITE microphones 26-1, 26-2, ... , 26-N are delayed in delays 44-1, 44-2, ... , 44-N after pre-processing in pre-processors 32-1, 32-2, ... , 32-N to compensate for the delays of the output signals from the M BTE microphones 14-1, 14-2, ... , 14-M caused by the adaptive cue filters 42-1, 42-2, ... , 42-M. The delays 44-1, 44-2, ... , 44-N may also be used for beamforming. The output signals from the N ITE microphones 26-1, 26-2, ... , 26-N are further combined in the signal combiner 64, e.g. as a weighted sum, and the output 52 of the signal combiner 64 is fed to a subtractor 54 analogous to the circuit of Fig. 7.

[0098] Likewise, the output signals from the M BTE microphones 14-1, 14-2, ... , 14-M are pre-processed in pre-processors 34-1, 34-2, ... , 34-M and filtered in the respective adaptive cue filters 42-1, 42-1, ... , 42-M and combined in the signal combiner 58, e.g. as a weighted sum, and the output 56 of the signal combiner 58 is fed to the subtractor 54 and the hearing aid processor 18 analogous to the circuit of Fig. 7.

[0099] The adaptive controller 48 controls the adaptation of the filter coefficients of adaptive cue filters 42-1, 42-1, ... , 42-M to minimize the difference 32 between the output of BTE signal combiner 58 and ITE signal combiner 64 provided by subtractor 54. In this way, the input signal 56 to the processor 18 models the microphone audio sound signal of the ITE microphones 26-1, 26-2, ... , 26-N, and thus also substantially models the HRTFs of the user.

[0100] The new BTE hearing aid circuitry shown in Fig. 8 may operate in the entire frequency range of the BTE hearing aid 10.

[0101] The BTE hearing aid 10 shown in Fig. 8 may be a multi-channel hearing aid in which microphone audio sound signals 38-1, 38-2, ... , 38-N, 40-1, 40-2, ... , 40-M to be processed are divided into a plurality of frequency channels, and wherein signals 38-1, 38-2, ... , 38-N, 40-1, 40-2, ... , 40-M are processed individually in each of the frequency channels.

[0102] For a multi-channel BTE hearing aid 10, Fig. 8 may illustrate the circuitry and signal processing in a single frequency channel. The circuitry and signal processing may be duplicated in a plurality of the frequency channels, e.g. in all of the frequency channels.

[0103] For example, the signal processing illustrated in Fig. 8 may be performed in a selected frequency band, e.g. selected during fitting of the hearing aid to a specific user at a dispenser's office.

[0104] The selected frequency band may comprise one or more of the frequency channels, or all of the frequency channels. The selected frequency band may be fragmented, i.e. the selected frequency band need not comprise consecutive frequency channels.

[0105] The plurality of frequency channels may include warped frequency channels, for example all of the frequency channels may be warped frequency channels.

[0106] Outside the selected frequency band, the at least one ITE microphone 26-1, 26-2, ... , 26-N may be connected conventionally as an input source to the signal processor 18 of the hearing aid 10 and may cooperate with the signal processor 18 of the hearing aid 10 in a well-known way.

[0107] In this way, the at least one ITE microphone 26-1, 26-2, ... , 26-N supplies the input to the hearing aid 10 at frequencies where the hearing aid 10 is capable of supplying the desired gain with this configuration. In the selected frequency band, wherein the hearing aid 10 cannot supply the desired gain with this configuration, the microphones 14-1, 14-2, ... , 14-M of BTE hearing aid housing are included in the signal processing as disclosed above. In this way, the gain can be increased while simultaneously maintain the spatial information about the sound environment provided by the at least one ITE microphone 26-1, 26-2, ... , 26-N.

[0108] As illustrated in Fig. 9 showing a hearing aid similar to the hearing aid of Fig. 8 except for the fact that a signal combiner 66 has been inserted in front of the processor 18 (not shown), comprising first filters connected between the processor input and the output of the signal combiner 64 of the at least one ITE microphone 26-1, 26-2, ... , 26-N, and second complementary filters connected between the processor input and the output of the signal combiner 58 of the at least one BTE microphone 14-1, 14-2, ... , 14-M, the filters passing and blocking, respectively, frequencies in complementary frequency bands so that the output of the signal combiner 64 of the at least one ITE microphone 26-1, 26-2, ... , 26-N constitutes the main part of the input signal supplied to the processor input in one or more first frequency bands, and the output of the signal combiner 58 of the at least one BTE microphone 14-1, 14-2, ... , 14-M constitutes the main part of the input signal supplied to the processor input in one or more complementary second frequency bands.

[0109] In this way, the at least one ITE microphone 26-1, 26-2, ... , 26-N may be used as the sole input source to the processor 18 in one or more frequency bands wherein the required gain for hearing loss compensation can be applied to the output signal of the at least one ITE microphone 26-1, 26-2, ... , 26-N. Outside these one or more frequency bands, the combined output signal 56 of the at least one BTE sound input transducer is applied to the signal processor 18 for provision of the required gain.

[0110] The combination of the signals could e.g. be based on different types of band pass filtering.

Claims

1. A BTE hearing aid (10) comprising
a BTE hearing aid housing to be worn behind the pinna of a user,
at least one BTE sound input transducer for conversion of acoustic sound into an audio sound signal,
a processor (16) configured to generate a hearing loss compensated output signal based on the audio sound signal,
a sound signal transmission member (34, 56) for transmission of a sound signal from a sound output in the BTE hearing aid housing (12) at a first end of the sound signal transmission member (34, 56) to the ear canal of the user at a second end of the sound signal transmission member (34, 56),
an earpiece configured to be inserted in the ear canal of the user for fastening and retaining the sound signal transmission member in its intended position in the ear canal of the user, and
an output transducer (20) for conversion of the hearing loss compensated output signal to an auditory output signal that can be received by the human auditory system,
an ITE microphone housing accommodating at least one ITE microphone and configured to be positioned in the outer ear of the user for fastening and retaining the at least one ITE microphone in its intended position,
characterized in
at least one adaptive cue filter, each of which having
an input that is provided with an output signal from a respective one of the at least one BTE sound input transducer, and the filter coefficients of which are adapted so that the difference between an output of the at least one ITE microphone and a combined output of the at least one adaptive cue filter is minimized.

2. A hearing aid (10) according to claim 2, wherein

the at least one BTE sound input transducer is constituted by a first and a second BTE sound input transducer, and the at least one adaptive cue filter is constituted by a first and second adaptive cue filter, wherein
the first adaptive cue filter has an input that is provided with an output signal from the first BTE sound input transducer, and
the filter coefficients of the first adaptive cue filter are adapted so that the difference between an output of the at least one ITE microphone and a combined output of the first and second adaptive cue filters is minimized.
the second adaptive cue filter has an input that is provided with an output signal from the second BTE sound input transducer, and
the filter coefficients of the second adaptive cue filter are adapted so that the difference between an output of the at least one ITE microphone and a combined output of the first and second adaptive cue filters is minimized.

3. A hearing aid (10) according to claim 2, wherein the filter coefficients of the at least one adaptive cue filter are adapted towards a solution of:

$$\min_{G_1^{BTEC}(f,t)\ldots G_n^{BTEC}(f,t)} \left\| W(f)(S^{IEC}(f,t) - G_1^{BTEC}(f,t)\, S_1^{BTEC}(f,t) - \right.$$

$$\ldots - G\boldsymbol{n}f,tS\boldsymbol{n}BTECf,t)p,$$

wherein
S^{IEC} *(f,t)* is the short time spectrum at time *t* of the output signal of the at least one ITE microphone, and

$S_1^{BTEC}(f,t),\ S_2^{BTEC}(f,t),\ \ldots\ ,S_n^{BTEC}(f,t)$ are the short time spectra at time *t* of the output signals of the at least one BTE sound input transducer, and

$G_1^{BTEC}(f,t),\ G_2^{BTEC}(f,t),\ \ldots\ ,G_n^{BTEC}(f,t)$ are the transfer functions of pre-processing filters connected to respective outputs of the at least one BTE sound input transducer, and
p is the norm factor, and
W(f) is a frequency weighting factor.

4. A hearing aid (10) according to claim 3, wherein p = 2.

5. A hearing aid (10) according to claim 3 or 4, wherein W(f) = 1.

6. A hearing aid (10) according to any of claims 3 - 5, having one ITE microphone and two BTE input sound transducers.

7. A hearing aid (10) according to any of the preceding claims, wherein the at least one adaptive filter is prevented from further adapting when the filter coefficient values have ceased changing significantly.

8. A hearing aid (10) according to any of the preceding claims, wherein the audio sound signals are divided into a plurality of frequency channels, and wherein the at least one adaptive cue filter is configured for individually processing the audio sound signals in selected frequency channels.

9. A hearing aid (10) according to claim 8, wherein the at least one BTE microphone is disconnected from the processor (16) in a selected frequency channel so that hearing loss compensation is based solely on the output of the at least one ITE microphone.

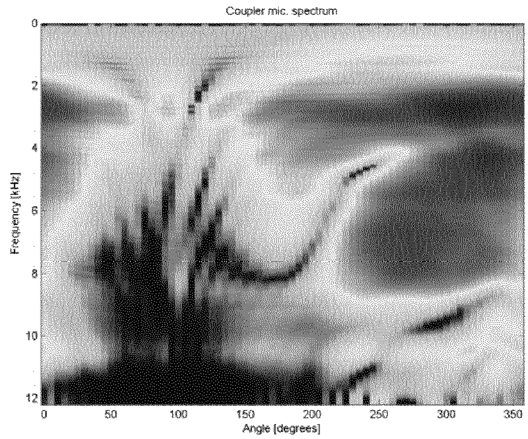


Fig. 1

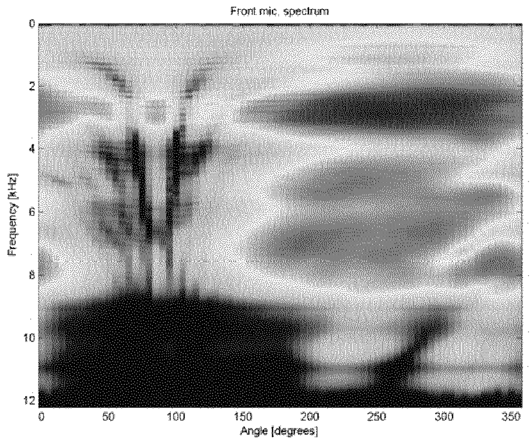


Fig. 2

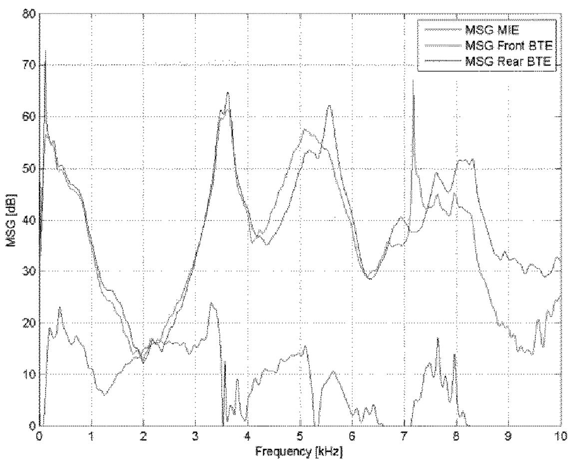


Fig. 3

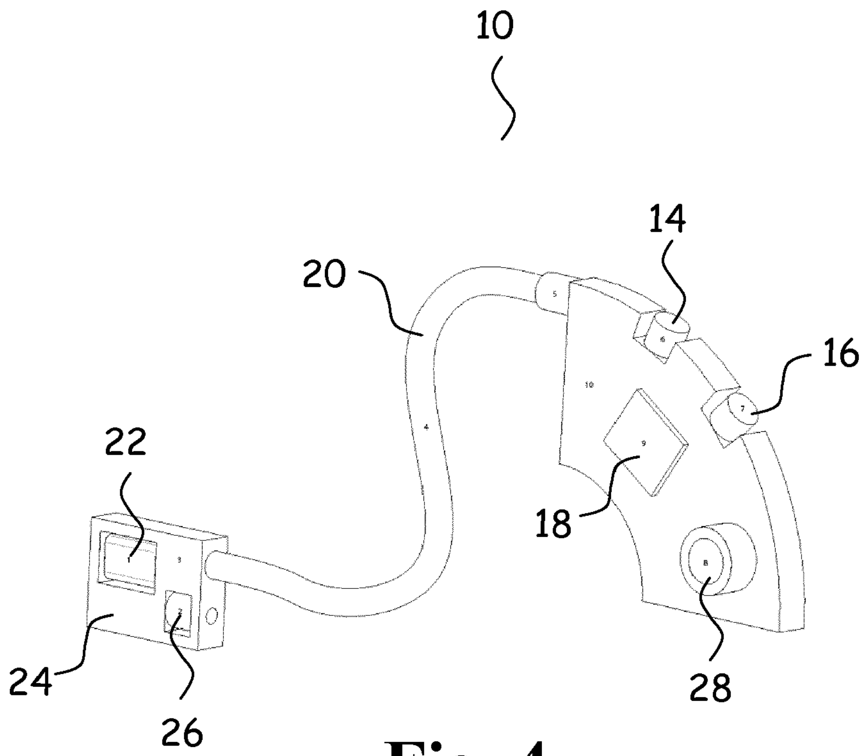


Fig. 4

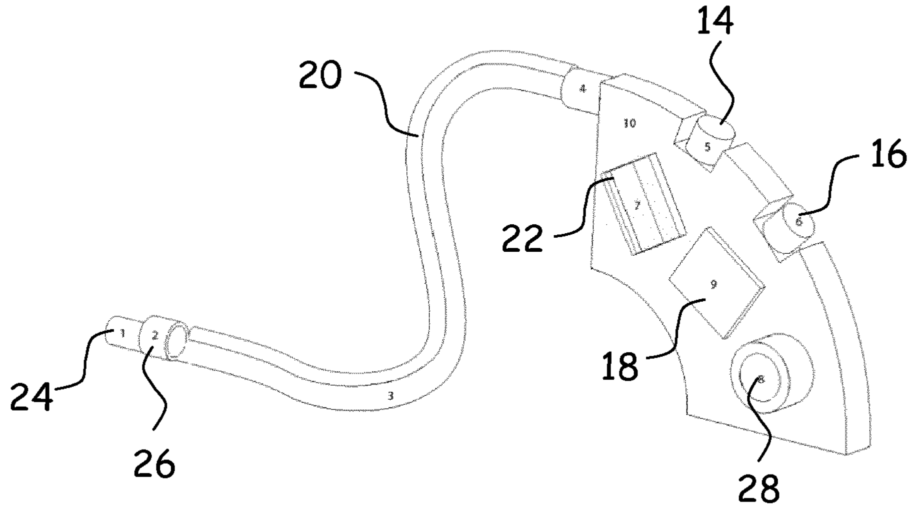


Fig. 5

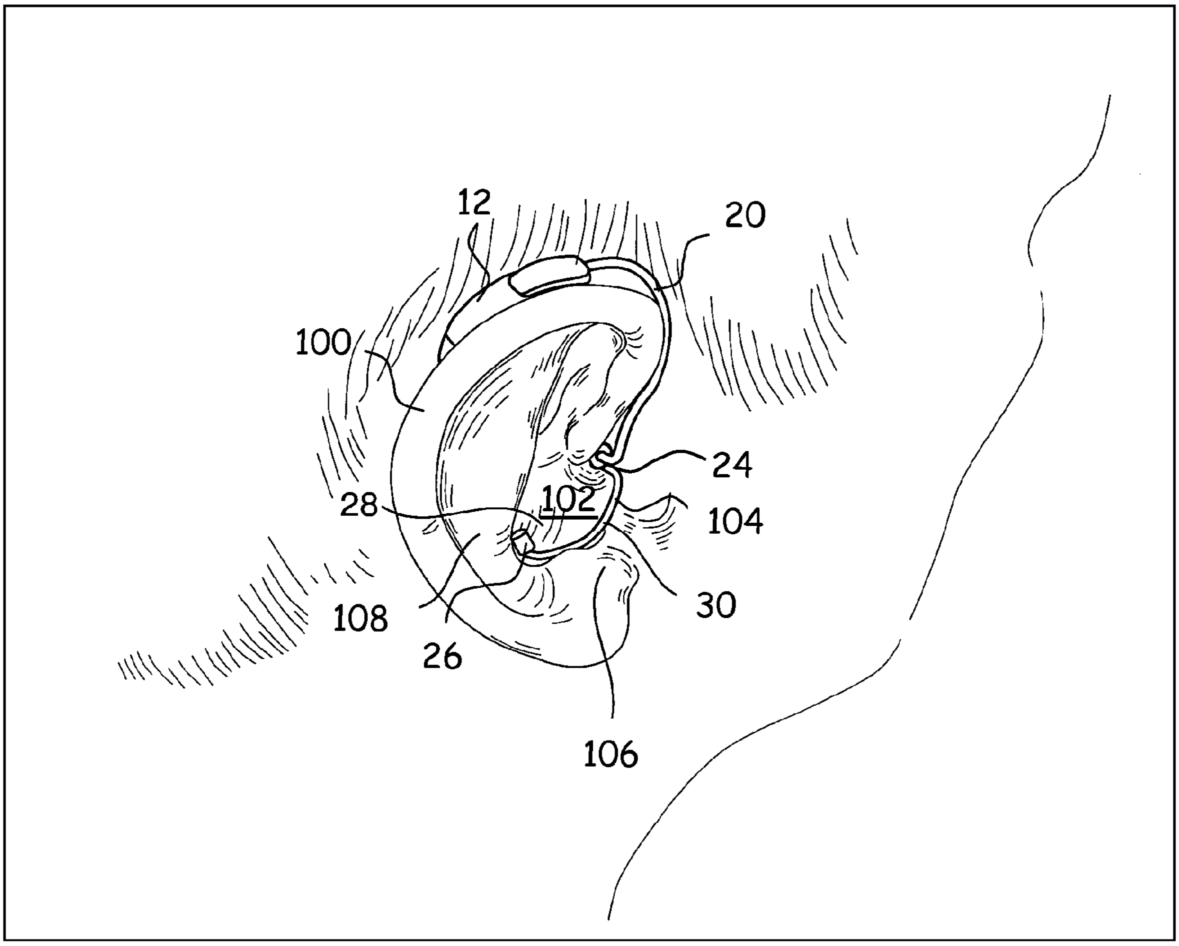
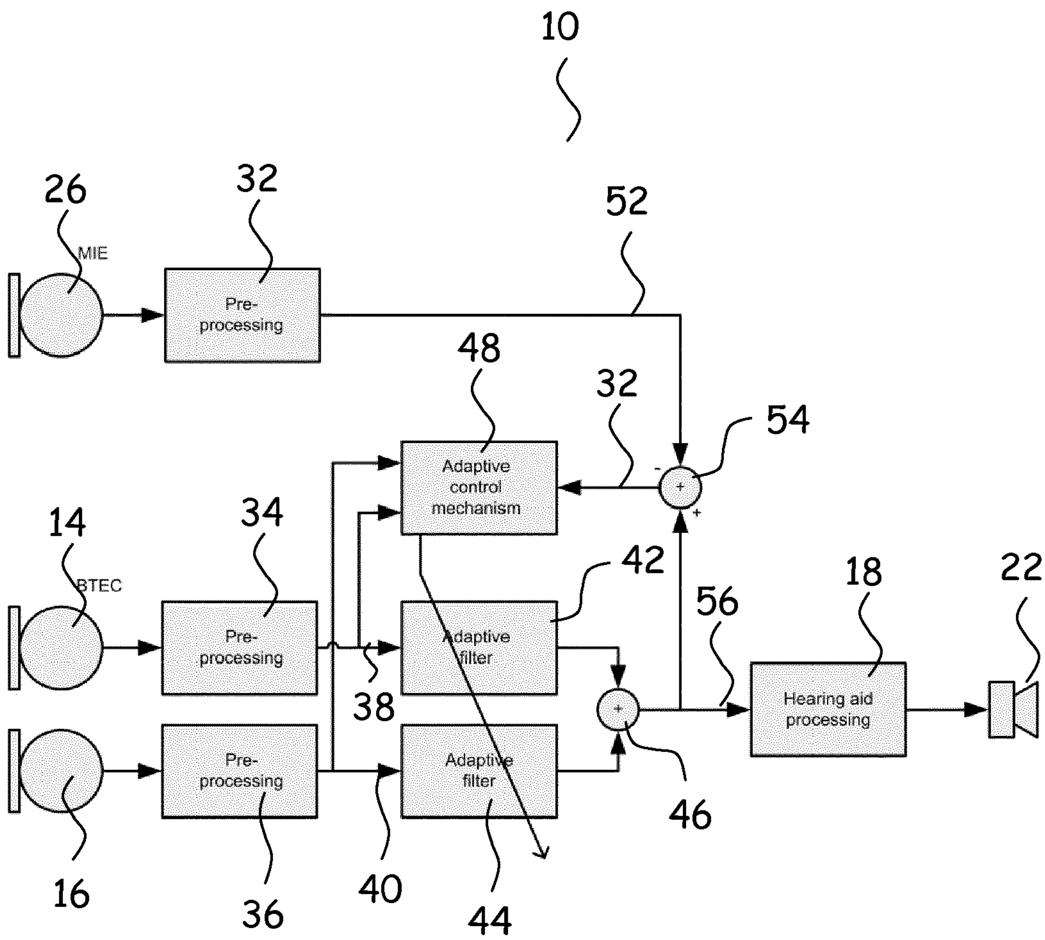


Fig. 6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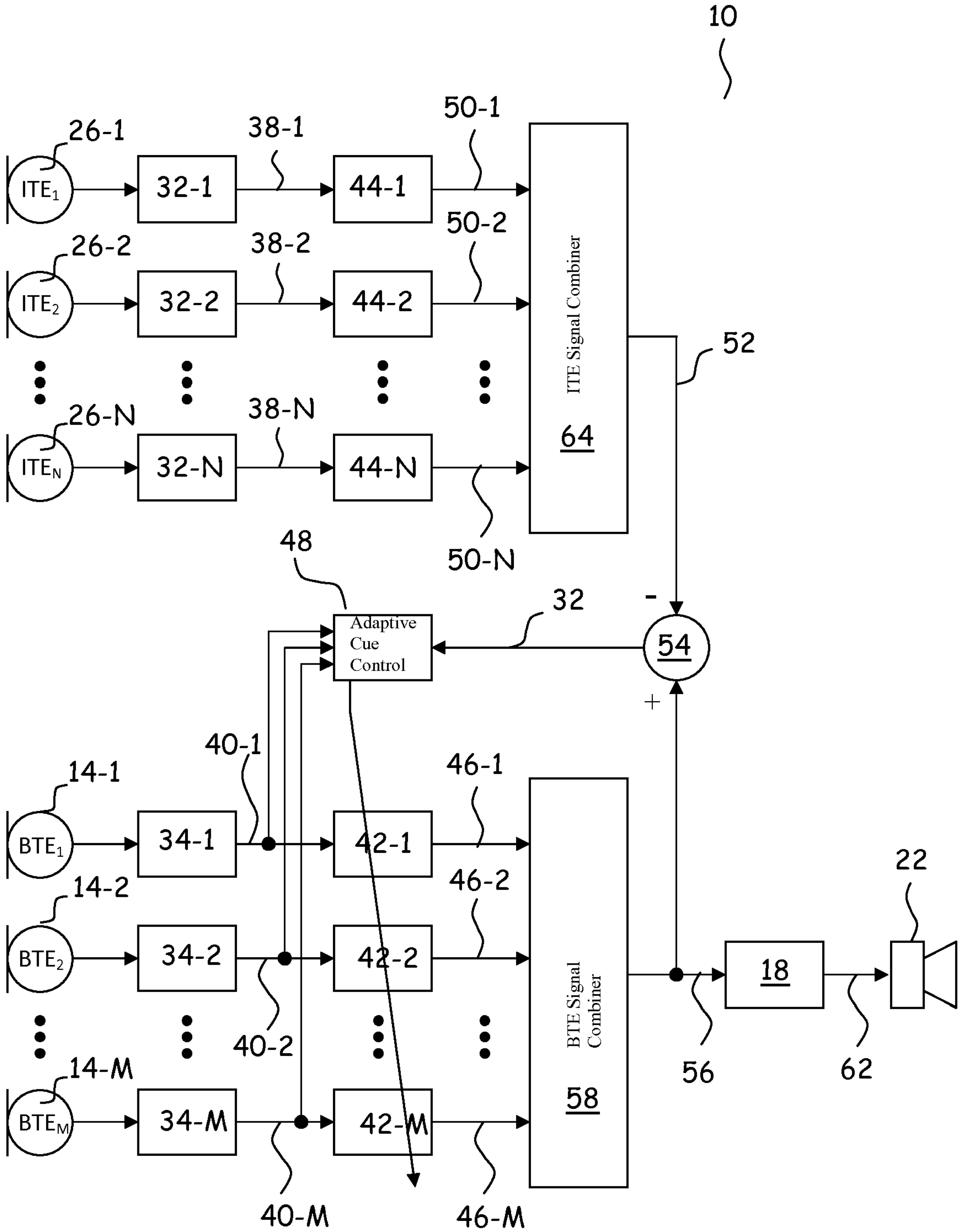
26
MIE
32
Pre-
processing
52
48
Adaptive
control
mechanism
32
54
14
BTEC
34
Pre-
processing
42
Adaptive
filter
56
18
Hearing aid
processing
22
38
Pre-
processing
Adaptive
filter
46
16
36
40
44

Fig. 7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26-1
ITE1
32-1
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ITE2
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ITE Signal Combiner
64
52
26-N
ITEN
32-N
38-N
44-N
50-N
48
Adaptive Cue Control
32
-
54
+
40-1
14-1
BTE1
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42-1
46-1
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BTE2
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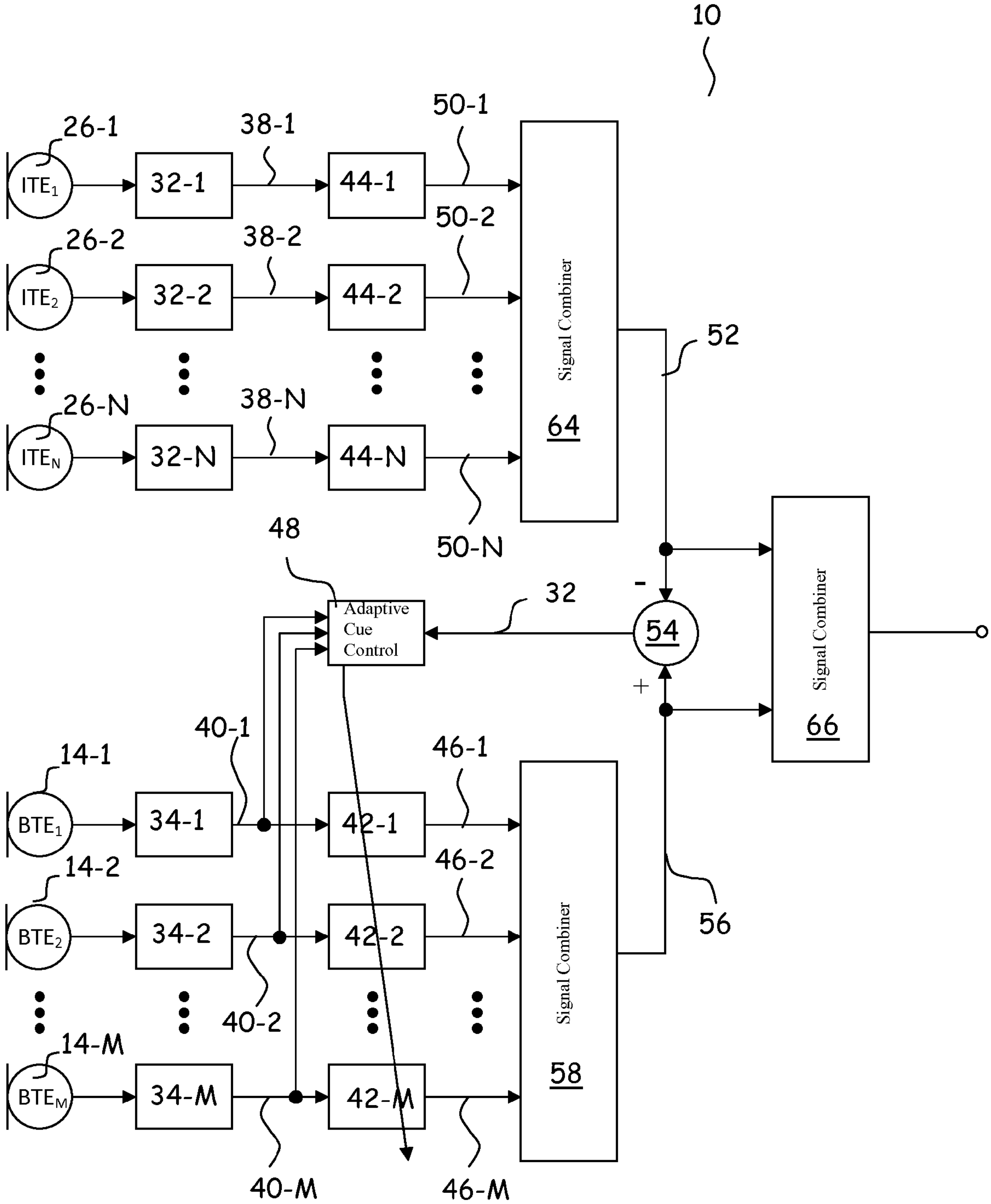
Fig. 8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BTEM
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46-M

Fig. 9

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EUROPEAN SEARCH REPORT

Application Number
EP 12 19 7705

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
A	EP 2 124 483 A2 (STARKEY LAB INC [US]) 25 November 2009 (2009-11-25) * column 1, paragraph 4 * * column 4, paragraph 18 - column 8, paragraph 32 * * claims 1-6,13-15; figures 1A,1B,2,4,5 * -----	1-9	INV. H04R25/00
A	EP 1 594 344 A2 (PHONAK AG [CH]) 9 November 2005 (2005-11-09) * page 7, paragraph 44 - page 9, paragraph 60 * * claims 1-11,15-24; figures 1-11 * -----	1-9	
A	EP 2 088 802 A1 (OTICON AS [DK]) 12 August 2009 (2009-08-12) * column 12, paragraph 59 - column 15, paragraph 76 * * figures 1-4 * -----	1-9	
A	EP 1 414 268 A2 (SIEMENS AUDIOLOGISCHE TECHNIK [DE]) 28 April 2004 (2004-04-28) * page 6, paragraph 27 - page 8, paragraph 38 * * page 10, paragraph 50 * * figures 1-4,7 * -----	1-9	TECHNICAL FIELDS SEARCHED (IPC) H04R

The present search report has been drawn up for all claims

1

Place of search	Date of completion of the search	Examiner
Munich	19 April 2013	Meiser, Jürgen

CATEGORY OF CITED DOCUMENTS

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19-04-2013

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
EP 2124483 A2	25-11-2009	EP 2124483 A2	25-11-2009
		US 2009290739 A1	26-11-2009
		US 2012308057 A1	06-12-2012
EP 1594344 A2	09-11-2005	NONE	
EP 2088802 A1	12-08-2009	AU 2008207437 A1	27-08-2009
		CN 101505447 A	12-08-2009
		EP 2088802 A1	12-08-2009
		US 2009202091 A1	13-08-2009
EP 1414268 A2	28-04-2004	DE 10249416 A1	19-05-2004
		DK 1414268 T3	21-05-2012
		EP 1414268 A2	28-04-2004
		US 2004136541 A1	15-07-2004

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