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

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
10 October 2013 (10.10.2013)

WIPO | PCT

(10) International Publication Number
WO 2013/151918 A1

(51) International Patent Classification:
H04R 1/10 (2006.01) *G10K 11/178* (2006.01)
H04R 3/02 (2006.01)

(21) International Application Number:
PCT/US2013/034772

(22) International Filing Date:
1 April 2013 (01.04.2013)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
13/437,083 2 April 2012 (02.04.2012) 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, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

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

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

(54) Title: INSTABILITY DETECTION AND AVOIDANCE IN A FEEDBACK SYSTEM

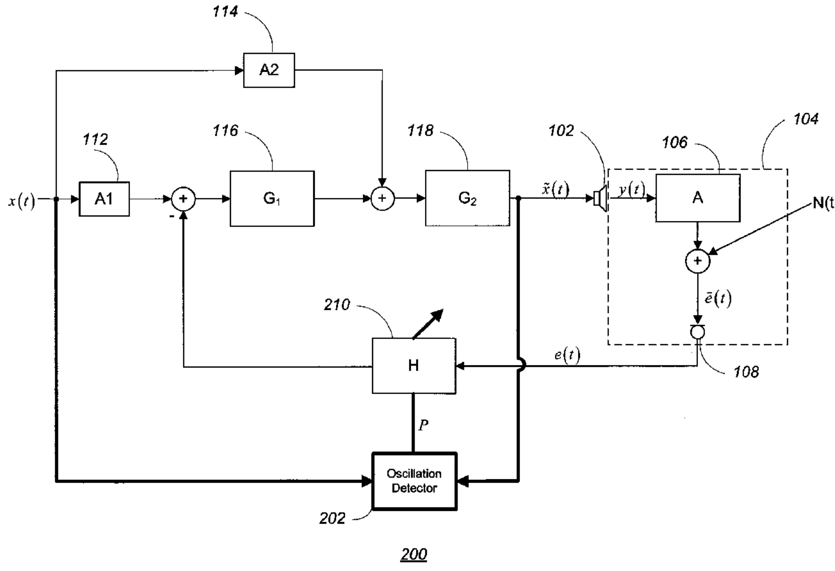

FIG. 1

(57) Abstract: A feedback based active noise reduction system is configured to detect actual or potential instability by detecting characteristics of the system related to potential or actual unstable behavior (e.g., oscillation) and adapt system characteristics to mitigate such instability.

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INSTABILITY DETECTION AND AVOIDANCE IN A FEEDBACK SYSTEM

Background

[001] This invention relates to instability detection and avoidance in a feedback system, in particular in a feedback active noise reduction system.

[002] The presence of ambient acoustic noise in an environment can have a wide range of effects on human hearing. Some examples of ambient noise, such as engine noise in the cabin of a jet airliner, can cause minor annoyance to a passenger. Other examples of ambient noise, such as a jackhammer on a construction site can cause permanent hearing loss. Techniques for the reduction of ambient acoustic noise are an active area of research, providing benefits such as more pleasurable hearing experiences and avoidance of hearing losses.

[003] Many conventional noise reduction systems utilize active noise reduction techniques to reduce the amount of noise that is perceived by a user. Active noise reduction systems are commonly implemented using feed-forward, feedback, or a combination of feed-forward and feedback approaches. Feedback based systems typically measure a noise sound wave, possibly combined with other sound waves, near an area where noise reduction is desired (e.g., in an acoustic cavity such as an ear cavity). In general, the measured signals are used to generate an “anti-noise signal” which is a phase inverted and scaled version of the measured noise. The anti-noise signal is provided to a noise cancellation driver which transduces the signal into a sound wave which is presented to the user. When the anti-noise sound wave produced by the noise cancellation driver combines in the acoustic cavity with the noise sound wave, the two sound waves cancel one another due to destructive interference. The result is a reduction in the noise level perceived by the user in the area where noise reduction is desired.

[004] Feedback systems generally have the potential of being unstable and producing instability based distortion. For example, as understood based on classical analysis of feedback systems, if the gain of a feedback loop is greater than 1 at a frequency where the phase of the feedback loop is 180°, oscillatory additive signals can be generated at that frequency. Such a situation can also be described as the phase margin, which is the margin to reach 180° phase at a frequency at which the gain is 1, of the system being zero or negative.

[005] In an acoustic active noise reduction system, at least a part of the feedback path can include an acoustic component. Although electrical or digital components of the feedback path can be directly controlled in an active noise reduction system, the acoustic component may be subject to variation, for example, as a result of variation in the physical characteristics of the acoustic path.

Summary

[006] In some cases, variation in the acoustic path may result in instability in the system due to resulting variation in the feedback loop gain or transfer function. For example, the acoustic component can have an acoustic transfer function between an acoustic driver and a feedback microphone. One example of a situation where the acoustic transfer function varies is when a wearer of an in-ear headphone inserts the earbud of the headphone into the ear canal. During the insertion process, the compliant tip of the earbud can become blocked, for example, by being pinched or folded over itself. Such a blocked tip can alter the acoustic transfer function, thereby altering the overall loop gain and potentially causing instability in the system.

[007] There is a need for a system which can detect characteristics of instability in a feedback noise reduction system and adjust the loop gain of the system to avoid instability.

[008] In one aspect, in general, an active noise reduction system detects actual or potential instability by detecting characteristics of the system related to potential or actual unstable behavior (e.g., oscillation) and adapts system characteristics to mitigate such instability.

[009] In some examples, the system adapts to variation in characteristics of an acoustic component of a feedback path that has or may induce unstable behavior to improve a user's acoustic experience.

[010] In another aspect, in general, a feedback based active noise reduction system includes a feedback component for forming at least part of a feedback loop having an audio path segment and an instability detector for detecting an instability condition in the feedback component and forming the control parameter based on a result of the detection. The feedback component includes a first signal input for accepting an input signal, a driver output for providing a driver signal to a driver of the audio path segment, a first feedback input for accepting a first feedback signal from a first sensor responsive to a signal on the audio path segment, and a control input for accepting a control parameter for adjusting at least one of a gain characteristic and a phase characteristic of the feedback loop. The instability detector includes a feedback loop signal input for accepting a feedback loop signal, a circuit for detecting an oscillatory signal component in the feedback loop signal not represented in the input signal, and a control parameter output for providing the control parameter to the control parameter input of the feedback element.

[011] Aspects may include one or more of the following features.

[012] The feedback loop signal may represent the driver signal. The feedback loop signal may represent the first feedback signal. The circuit for detecting the oscillatory signal component in the feedback loop signal may include a circuit for forming a modified feedback loop signal, the circuit including circuitry for removing a component of the input signal from the feedback loop signal, and a circuit for detecting the oscillatory signal component in a specified frequency range in the modified feedback loop signal.

[013] The circuit for detecting the oscillatory signal component may include a voltage controlled oscillator and a circuit for combining an output of the voltage controlled oscillator and the modified feedback loop signal. The feedback component may include a feed-forward input for accepting a first feed-forward signal from a second sensor responsive to a second signal on the audio path segment. The circuit for detecting the oscillatory signal component in the feedback loop signal may include a high-pass filter for removing an active noise reduction signal component from the feedback loop signal. The circuit for forming the modified feedback loop signal may include a filtering element for forming the component of the input signal, and a signal combiner for removing the component of the input signal from the feedback loop signal.

[014] The filtering element may include a control parameter input for accepting the control parameter for adjusting a gain and phase characteristic of the filtering element. The circuit for detecting the oscillatory signal may include a phase locked loop (PLL).

[015] In another aspect, in general, a method for feedback based active noise reduction includes accepting, at a first signal input of a feedback component, an input signal, the feedback component forming at least part of a feedback loop having an audio path segment, providing, through a driver output of the feedback component, a driver signal to a driver of the audio path segment, accepting, at a first feedback input of the feedback component, a first feedback signal from a first sensor responsive to a signal on the audio path segment, accepting, at a control input of the feedback component, a control parameter for adjusting at least one of a gain characteristic and a phase characteristic of the feedback loop, and detecting an instability condition in the feedback component and forming the control parameter based on a result of the detection. Detecting the instability condition includes accepting, at a feedback loop signal input, a feedback loop signal, detecting an oscillatory signal component in the feedback loop signal, the oscillatory signal component not represented in the input signal, and providing, through a control parameter output, the control parameter to the control parameter input of the feedback element.

[016] Aspects may include one or more of the following features.

[017] The feedback loop signal may represent the driver signal. The feedback loop signal may represent the first feedback signal. Detecting the oscillatory signal component in the feedback loop signal may include forming a modified feedback loop signal, including removing a component of the input signal from the feedback loop signal, and detecting the oscillatory signal component in a specified frequency range in the modified feedback loop signal. Detecting the oscillatory signal component may include combining an output of a voltage controlled oscillator and the modified feedback loop signal. The method may also include accepting, at a feed-forward input, a first feed-forward signal from a second sensor responsive to a second signal on the audio path segment.

[018] Detecting the oscillatory signal component in the feedback loop signal may include applying a high-pass filter to the feedback loop signal for removing an active noise reduction signal component from the feedback loop signal. Forming the modified feedback loop signal may include, forming the component of the input signal at a filtering element and removing the component of the input signal from the feedback loop signal at a signal combiner. Forming the component of the input signal at the filtering element may include accepting, at a control parameter input of the filtering element, the control parameter for adjusting a gain and phase characteristic of the filtering element. Detecting the oscillatory signal may include using a phase locked loop (PLL) for detecting and tracking the oscillatory signal.

[019] Embodiments may have one or more of the following advantages.

[020] Embodiments may require few electronic parts, resulting in a reduced cost relative to conventional systems which include general purpose digital signal processing (DSP) hardware.

[021] Embodiments may consume very little power (e.g., micro-watts) since they do not require high speed/low noise operational amplifiers.

[022] Embodiments may react to disturbances more quickly than DSP based systems which require long measurement and calculation times. In some examples DSP based systems do not react quickly enough to prevent a loud, high pitched sound from impinging on the eardrum for an extended duration due to the close proximity of the loudspeaker driver to the eardrum in a headphone device.

[023] Embodiments are immune to being triggered by audio signals alone, and can reliably detect oscillation in the presence of audio signals.

[024] Embodiments can track frequency modulations of an oscillatory signal.

[025] Other features and advantages of the invention are apparent from the following description, and from the claims.

Description of Drawings

[026] FIG. 1 is a block diagram of a feedback noise reduction system including an oscillation detector.

[027] FIG. 2 is a block diagram of an oscillation detector.

[028] FIG. 3 is a graph showing gain and phase margin.

[029] FIG. 4 is a overview of a circuit configured to reduce loop gain which is shown in detail in FIGs. 4a, 4b, and 4c.

[030] FIG. 4a is a detailed view of a portion of the circuit configured to reduce loop gain.

[031] FIG. 4b is a detailed view of a portion of the circuit configured to reduce loop gain.

[032] FIG. 4c is a detailed view of a portion of the circuit configured to reduce loop gain.

[033] FIG. 5 is a graph showing gain and phase margin.

[034] FIG. 6 is a circuit configured to reduce loop gain and bandwidth.

[035] FIG. 7 is an in-ear headphone with a blocked tip.

[036] FIG. 8 is a graph of acoustic impedance for an unblocked case and a blocked case.

[037] FIG. 9 is an in-ear headphone configured to detect a blocked tip.

[038] FIG. 10 is a block diagram of a feedback noise reduction including a combined oscillation/blocked tip detector.

[039] FIG. 11 is a block diagram of a combined oscillation/blocked tip detector.

[040] FIG. 12 is a truth table showing the logic used to compute the output of the combined oscillation/blocked tip detector.

[041] FIG. 13 is a graph of an acoustic impedance metric for an unblocked case and a blocked case.

[042] FIG. 14 is a block diagram of a second feedback noise reduction system including an oscillation detector.

[043] FIG. 15 is a block diagram of a second oscillation detector.

[044] FIG. 16 is a block diagram of a gain controller.

[045] FIG. 17 is a block diagram of a third feedback noise reduction system including an oscillation detector.

[046] FIG. 18 is a second combined oscillation/blocked tip detector.

Description

1 Overview

[047] The system described herein detects actual or potential feedback loop instability due to excessive feedback loop gain in a feedback control based active noise reduction system and mitigates the instability to return the system to a stable or more stable operating state.

[048] The system leverages the knowledge that:

a) as the gain of the feedback loop approaches 1 at a frequency where the phase of the feedback loop approaches $180°$, the bandwidth of the gain of the feedback loop increases. This reduces the phase margin in the system, ultimately resulting in an unstable feedback loop which can result in oscillation or damped oscillation at that frequency.

b) when the tip of an earbud is obstructed, a significant change in acoustic impedance occurs, altering the feedback loop gain.

[049] Upon detection of instability in the feedback loop, the system mitigates the instability by adjusting the gain of the feedback loop.

2 Oscillation Detector

[050] Referring to FIG. 1, a system for acoustic active noise reduction 200 receives an input signal (e.g., an audio signal), $x(t)$ and provides a modified version of the input signal, to an acoustic driver 102. The acoustic driver 102 transduces the modified version of the input signal into a sound wave, $y(t)$, in an acoustic cavity 104. In the acoustic cavity 104, $y(t)$ passes through an acoustic transfer function, A 106, between the acoustic driver 102 and a feedback microphone 108. The result of $y(t)$ passing through A 106, combines with a noise sound wave, $N(t)$, to produce $\tilde{e}(t)$. The feedback microphone 108 measures $\tilde{e}(t)$, transducing the sound wave into an electrical signal, $e(t)$. This signal is passed along a feedback path, through a feedback factor, H 210.

[051] In a forward path, the input signal, $x(t)$ is provided to a first transfer function block, A_1 112. The output of the feedback factor H 210 is then subtracted from the output of the first transfer function block 112. In some examples, the output of A_1 112 includes only (or predominantly) the frequency components of $x(t)$ that are within a desired active noise reduction bandwidth, with the frequencies that are outside the desired active noise reduction bandwidth attenuated. The result of the subtraction is provided to first forward path gain element, G_1 116.

[052] In parallel, the input signal, $x(t)$, is provided to a second transfer function block, A_2 114. The output of the first forward path gain element G_1 116 is added to the output of the second transfer function block 114. In some examples, the output of A_2 114 includes only the frequency components of $x(t)$ that are outside the desired active noise reduction bandwidth, with the frequencies that are within the desired active noise reduction bandwidth attenuated. The result of the addition is provided to a second forward path gain element, G_2 118. The output of the second forward path element G_2 118 is provided to the acoustic driver 102.

[053] In some examples, the purpose of injecting different components of the input signal, $x(t)$ into the forward path at different stages is to apply higher gain to components of the input signal which are deemed as more important. For example, the system of FIG. 1 injects the frequency components of $x(t)$ that are within the active noise reduction bandwidth earlier in the system than those frequency components of $x(t)$ that are outside of the active noise reduction bandwidth. This results in the application of more gain (i.e., both G_1 116 and G_2 118) to the frequency components that are within the active noise reduction bandwidth and the application of less gain (i.e., only G_2 118) to the frequency components that are outside the active noise reduction bandwidth. Higher feedback gain results in greater noise reduction.

[054] In some examples, $x(t)=0$ (i.e., no input signal is provided). In such examples, the active noise reduction system reduces ambient noise at the feedback microphone, driving the signal sensed at the microphone to zero.

[055] In the system shown in FIG. 1, $e(t)$ is a measurement of the acoustic signal in the acoustic cavity at the location of the feedback microphone 108. In the frequency domain, $e(t)$ can be expressed as $E(\omega)$ as follows:

$$E(\omega)=\frac{G_1G_2A_1AX(\omega)+G_2A_2AX(\omega)+N(\omega)}{1+G_1G_2HA}$$

[056] The G_1G_2HA term in the denominator is commonly referred to as the feedback loop gain. It is noted that while this term is referred to herein as the "loop gain", the term should be understood as a loop characteristic, including both a frequency dependent gain response of the feedback loop and a frequency dependent phase response of the feedback loop. Thus, a statement such as: "the loop gain equals $1\angle 180°$" should be understood as a loop characteristic where the loop gain at a frequency is equal to 1 and the loop phase is equal to $180°$.

[057] By inspection, one can see that as the gain of the first and second forward path gain elements 116, 118 becomes very large, the noise term, $N(\omega)$ is reduced. In this way, noise reduction in the system of FIG. 1 is accomplished using a high loop gain.

[058] Also note that as the first and second forward path gain elements 116, 118 become very large, the $G_1G_2A_1AX(\omega)$ term is less affected by the high loop gain than the $G_2A_2AX(\omega)$ term as is expected due to the two injection points of the input signal, $x(t)$.

[059] Referring to the portions of FIG. 1 shown in bolded lines, the system includes an oscillation detector 202 that is configured to detect oscillations at the frequency where the loop gain equals $1\angle 180°$. If an oscillation is detected, the oscillation detector 202 can trigger a loop gain adjustment to return the feedback loop to a stable operating state.

[060] The oscillation detector 202 receives the input signal $x(t)$ and the output of the second forward path gain element 118, $\tilde{x}(t)$ and outputs a control parameter, P to the adjustable feedback factor, H 210. The control parameter, P indicates whether oscillations that are due to instability are present in the feedback loop and commands the feedback factor, H 210 (e.g., by outputting P=HIGH) to adjust the loop gain if necessary.

[061] Referring to FIG. 2, the oscillation detector 202 processes $\tilde{x}(t)$ and $x(t)$ and compares the resulting processed signals to determine if oscillations are present in the feedback loop that are not present in the input signal. The processing of the signals is based on the knowledge that an oscillation signal due to feedback loop instability typically occurs in a frequency range where the loop gain is near $1\angle 180°$. Furthermore, it is typical that active noise reduction signals are present at lower frequencies than the oscillation signal.

[062] The oscillation detector 202 processes $\tilde{x}(t)$ and $x(t)$ in two separate paths. A driver signal path 302 applies a band-pass filter 304 to $\tilde{x}(t)$, the band-pass filter 304 having a pass-band at the frequency range where oscillation due to instability is expected. The filtered output of the band-pass filter 304 is rectified by a full wave rectifier 306 and smoothed by a smoothing element 308 (e.g., a low pass filter). The result of the driver signal path 302 is a signal level of $\tilde{x}(t)$ in the frequency range where oscillation due to instability is expected.

[063] In the absence of the input signal, $x(t)$, (i.e., when no audio driving signal is provided) the driver signal path 302 is sufficient for detecting oscillations due to instability in the feedback loop. However, in the presence of the input signal, $x(t)$ it is necessary to process both $x(t)$ and $\tilde{x}(t)$. This is due to the fact that the input signal $x(t)$ (e.g., an audio signal), may include frequency components which are present in the frequency range where oscillation is expected. In the presence of such an input signal, false instability detection results may occur.

[064] Thus, to improve the robustness of the system, $x(t)$ is processed in a reference signal path 310 for the purpose of establishing a dynamic threshold reference. The reference signal path applies a band-pass filter 312 to $x(t)$, the band-pass filter 312 having a pass band at the frequency range where oscillation due to instability is expected. The filtered output of the band-pass filter 312 is rectified by a full wave rectifier 314 and smoothed by a smoothing element 316 (e.g., a low pass filter).

[065] The output of the smoothing element 316 is a signal level of $x(t)$ in the frequency range where oscillation due to instability is expected. This output is scaled by a scale factor, K 318, such that the output of the reference signal path 310 is slightly greater than the output of the driver signal path 302 when $x(t)$ is present and no oscillation is present in the feedback loop.

[066] The output of the driver signal path 302 and the output of the reference signal path 310 are provided to a differential detector 320 which outputs a value of $P = \text{HIGH}$ if the output of the driver signal path 302 is greater than the output of the reference signal path 310 (i.e., oscillation is present) and a $P = \text{LOW}$ if the output of the driver signal path 302 is less than the output of the reference signal path 310 (i.e., no oscillation is present).

3 Adjustable Feedback Factor

[067] Parameter P (e.g., a HIGH or LOW output) output by the oscillation detector 202 is provided to the adjustable feedback factor, H (FIG. 1, element 210). In some examples, the adjustable feedback factor 210 is adjusted, based on the parameter P to modify the overall feedback loop gain of the system across all or a wide range of frequencies. In other examples, the adjustable feedback factor 210 is adjusted, based on the parameter P to modify the bandwidth of the feedback loop gain, for example by reducing the gain over a limited range of frequencies. In some examples, the modification of the feedback loop gain is maintained for a predetermined amount of time. After the predetermined amount of time (e.g., 3 seconds) has elapsed, the modification of the feedback loop gain is reversed.

3.1 Overall Gain Adjustment

[068] Referring to FIG. 3, an example of a feedback loop gain and phase response illustrates an unstable situation in the feedback loop of the system of FIG. 1. In particular, the feedback loop is in an unstable situation due to the solid gain curve 420 being equal to 1 and the solid phase curve 422 being equal to 180° at the frequency ω_u. In this situation, the phase margin is 0°, causing instability.

[069] In some examples, the adjustable feedback factor 210 is configurable to mitigate this instability by reducing the gain by a predetermined amount based on the parameter P received from the instability detector 202. In particular, if P indicates that the phase margin is at or near 0° (i.e., the instability detector outputs a HIGH parameter value), the feedback factor reduces the overall gain by a predetermined amount.

[070] The dashed gain curve 424 is the result of an overall reduction of the feedback loop gain. Since the phase curve 422 is not changed, reducing the overall loop gain results in an increased phase margin 426, returning the feedback loop to a stable operating state.

[071] Referring to FIGs. 4, 4a, 4b, and 4c, a circuit is configured to reduce the overall loop gain passed on P. The overall reduction in loop gain is achieved by a P=HIGH output from the instability detector 202 turning on a mosfet 530 at the feedback microphone 108, thereby reducing the loop gain at the feedback microphone input 108.

3.2 Bandwidth Adjustment

[072] Referring to FIG. 5, another example of a feedback loop gain and phase response illustrates an unstable situation in the feedback loop of the system of FIG. 1. In particular, the feedback loop is in an unstable situation due to a first gain curve 620 having a value of 0 dB at a frequency, ω_u, where a first phase curve 622 has a value close to -180°. In this situation, the phase margin is reduced, causing instability.

[073] In some examples, the adjustable feedback factor 210 is configurable to switch the feedback loop gain between a high bandwidth mode and a low bandwidth mode based on the parameter P. The high bandwidth mode is used during normal operation of the system and the low bandwidth mode is used when a system change places the system in a potentially unstable operating state. If the parameter, P indicates that the bandwidth of the feedback loop needs to be reduced (i.e., the instability detector outputs a P=HIGH parameter value), the adjustable feedback factor enables a low-pass filtering operation in the feedback path.

[074] A second loop gain curve 624 shows a reduction in the loop gain at high frequencies with little effect on the loop gain at low frequencies. Such a reduction in the bandwidth of the loop gain results in an increased the phase margin 626 while having less impact on the audio output quality of the system when compared to the previously described overall reduction in loop gain.

[075] Referring to FIG. 6, one example of the adjustable feedback factor 210 achieves the low bandwidth mode of the feedback loop gain by switching in a simple pole-zero low pass network 740 into the existing high bandwidth feedback loop upon detection of a potentially unstable operating state.

[076] For example, the parameter output, P of the instability detector (FIG. 1, element 202) can be provided to mosfet, M1 742 such that a HIGH parameter value switches M1 742 to an on state. When M1 742 is on, an RC network 744, 746 is switched into the system. The RC network 744, 746, along with the effective output impedance 748 of the feedback microphone 108 forms a low-pass filter.

[077] The low-pass filter formed by the RC network 744, 746 and the effective impedance 748 of the feedback microphone 108 includes a zero break (caused by the inclusion of resistor R331 744). The zero break halts phase lag in the low-pass filter at higher frequencies, resulting in a higher stability margin.

[078] The adjustable feedback factor 210 described above can be implemented using analog or digital electronics. In some examples, the parameter output P of the instability detector 202 is used to switch a compensation filter with a different transfer function than those described above into the system. In some examples a different compensation filter is used based on whether the adjustable feedback factor is implemented using analog electronics or digital electronics (e.g., dedicated DSP hardware).

4 Blocked Tip Detection

[079] Referring to FIG. 7, an earbud 850 of an active noise reduction headphone system is configured to be inserted into an ear canal 852 of a wearer 854. When inserted, the earbud 850 presses outward against the inner walls of the wearer's ear canal 852, creating a sealed cavity 856 within the ear canal 852. The earbud 850 includes an inner cavity 858 which extends from an acoustic driver 860 in the earbud into the sealed cavity 856 within the ear canal 852.

[080] At the end of the inner cavity 858 of the earbud 850 opposite the acoustic driver a blockage 862 obstructs the opening of the inner cavity 858 into the cavity 856 within the ear canal 852. Such a blockage 862 commonly arises while the wearer 854 is inserting the earbud 850 into the ear canal 852 and can be referred to as a “blocked tip.”

[081] Referring to FIG. 8 one indication of a blocked tip is increased acoustic impedance in the inner cavity (FIG. 7, element 858) of the earbud (FIG. 7, element 850). The On-Head curve 970 in the graph shows the acoustic impedance of an earbud 850 without a blocked tip and the Blocked Tip curve 972 in the graph shows the acoustic impedance of an earbud 850 with a blocked tip. By inspection it is easily ascertained that the acoustic impedance in the blocked tip case is significantly increased.

[082] Referring to FIG. 9, one method of detecting such a change in acoustic impedance is to use a velocity microphone 1080 in addition to the pressure microphone 1082 that is already used as the feedback microphone (FIG. 1, element 108) for the active noise reduction system (i.e., the system of FIG. 1).

[083] The equation for acoustic impedance is:

$$z = \frac{\text{Pressure}}{\text{Velocity}}$$

[084] Thus, acoustic impedance is determined by placing the velocity microphone 1080 in close proximity to the pressure microphone 1082 and calculating a ratio between the two microphone signals in a specified frequency range. If the acoustic impedance is determined to exceed a predetermined threshold, the tip of the earbud is likely blocked.

[085] This method is not influenced by the nature of the sound waves emitted by the acoustic driver 860 inside the inner cavity 858 of the earbud 850 (e.g., noise, speech, audio). However, to calculate the ratio, sufficient acoustic signal must be present in the inner cavity 858 of the earbud 850.

[086] To determine whether sufficient acoustic signal is present in the inner cavity 858 of the earbud, an additional pressure microphone 1084 can be included in the earbud 850 such that it is outside of both the inner cavity 858 of the earbud 850 and the cavity within the ear canal 856. This microphone 1084 can detect the pressure outside of the ear cavity 856 and use it to determine whether the calculated impedance is reliable. For example, the calculated impedance is considered reliable if the outside pressure exceeds a certain predetermined threshold.

Combined Oscillation and Blocked Tip Detector

[087] Referring to FIG. 10, the oscillation detector 202 of the system of FIG. 1, is augmented with the blocked tip detection algorithm described above, resulting in a system 1100 which includes a combined oscillation/blocked tip detector 1110.

[088] The basic operation of the feedback loop of the system 1100 is much the same as was described in reference to the feedback loop of the system 100 shown in FIG. 1 and therefore will not be repeated in this section.

[089] The combined oscillation/blocked tip detector 1110 receives input from the input signal, $x(t)$ the driver output signal $\tilde{x}(t)$, the feedback pressure microphone, M1 108, a feedback velocity microphone, M2 1080, and an outside pressure microphone, M3 1084. The output of the combined oscillation/blocked tip detector 1110 is a parameter, P which has a value of HIGH if either oscillations due to instability or a blocked tip is detected. Otherwise, P has a value of LOW. As was described above with respect to the system of FIG. 1, P is provided to the adjustable feedback factor H 210 which in turn adjusts the feedback loop gain or bandwidth to mitigate instability in the feedback loop.

[090] Referring to FIG. 11, a detailed block diagram of the oscillation/blocked tip detector 1110 includes the oscillation detector 1202 described above, a blocked tip detector 1204, and an outside pressure detector 1206. The results of the oscillation detector 1202, blocked tip detector 1204, and outside pressure detector 1206 are processed using Boolean logic 1208 to produce a HIGH parameter value if an oscillation or a blocked tip is detected. Otherwise the Boolean logic 1208 produces a LOW parameter value.

[091] The blocked tip detector 1204 receives as input the feedback pressure microphone signal $M1(t)$ and the velocity microphone signal $M2(t)$. $M1(t)$ is filtered by a first band-pass filter 1210, rectified by a first full wave rectifier 1212, and smoothed by a first smoothing element 1214. $M2(t)$ is filtered by a second band-pass filter 1216, rectified by a second full wave rectifier 1218, and smoothed by a second smoothing element 1220.

[092] Band-pass filtering, rectification, and smoothing of the microphone input signals $M1(t)$ and $M2(t)$ results in an estimate of the signal level in a frequency of interest (e.g., a frequency where it is known that a blocked tip significantly increases acoustic impedance). The processed versions of $M1(t)$ is divided by the processed version of $M2(t)$, yielding an estimate of the acoustic impedance in the vicinity of the microphones (FIG. 10, elements 108, 1080). The estimate of the acoustic impedance is compared to an acoustic impedance threshold, V_{Z_Ref}. If the estimate of the acoustic impedance is greater than the reference threshold, the blocked tip detector 1204 outputs a HIGH value indicating that the tip is likely blocked. Otherwise, the blocked tip detector outputs a LOW value.

[093] The outside pressure level detector 1206 receives as input the outside pressure microphone signal $M3(t)$. $M3(t)$ is filtered by a third band-pass filter 1222, rectified by a third full wave rectifier 1224, and smoothed by a third smoothing element 1226. The output of the third smoothing element 1226 is an estimate of the sound pressure level outside of the ear cavity. The estimate of the sound pressure level outside of the ear cavity is compared to a outside pressure threshold V_{Pout_Ref}. If the estimate of the sound pressure level outside of the ear cavity is greater than the outside pressure threshold, the outside pressure level detector 1206 outputs a HIGH value indicating that result of the blocked tip detector 1204 is valid. Otherwise, the outside pressure level detector 1206 outputs a LOW value indicating that the result of the blocked tip detector 1204 is invalid.

[094] The HIGH or LOW outputs of the blocked tip detector 1204, oscillation detector 1202, and the outside pressure level detector 1206 are used as input to Boolean logic 1208 which determines the output, P of the blocked tip/oscillation detector 1110.

[095] Referring to FIG. 12, a truth table illustrates the result of applying the following Boolean logic to the outputs of the blocked tip detector 1204, oscillation detector 1202, and outside pressure level detector 1206:

$$P = \text{BlockedTipDetector} \vee (\overline{\text{OutsidePressureDetector}} \wedge \text{OscillationDetector})$$

6 Alternatives

6.1 Alternative Microphone Configuration

[096] Referring to FIG. 13, in some examples, instead of using a velocity microphone in conjunction with the feedback pressure microphone to calculate acoustic impedance, a second pressure microphone is placed inside the cavity (e.g., near the tip of the nozzle). The acoustic impedance can be calculated as the ratio $P1/(P1-P2)$. FIG. 13 shows impedance curves calculated using this method. Curve 1402 is the impedance curve representing an unblocked tip. Curve 1404 is the impedance curve representing a blocked tip.

[097] In some examples, a change in acoustic impedance is detected by monitoring the electrical input impedance at the driver. In some examples, due to characteristics of the driver an acoustic to electric transformation ratio is relatively small, resulting in a poor signal to noise ratio. However, characteristics of the driver can be adjusted to yield a larger acoustic to electric transformation ratio resulting in an improved signal to noise ratio.

6.2 Alternative Embodiment #1

[098] Referring to FIG. 14, another embodiment of a system for acoustic active noise reduction 1500 includes two features not described above for the embodiment of a system for acoustic active noise reduction 200 of FIG. 1.

[099] The first feature is that the system for acoustic active noise reduction 1500 shown in FIG. 14 includes a feed-forward microphone 1503 which transduces sound into a feed-forward signal, $z(t)$, which is passed to a feed-forward transfer function block, G_3 1501. The outputs of G_3 1501, the first transfer function block, A_1 112, and the feedback factor, H 210 are combined and provided to the first forward path gain element, G_1 116, as is the case in FIG. 1. Thus, in this embodiment, $e(t)$ can be expressed as $E(\omega)$ in the frequency domain as follows:

$$E(\omega)=\frac{G_1G_2A_1AX(\omega)+G_2A_2AX(\omega)+G_1G_2G_3AZ(\omega)+N(\omega)}{1+G_1G_2HA}$$

[0100] The second feature is that the system for acoustic active noise reduction 1500 shown in FIG. 14 includes an oscillation detector 1502, that operates differently than the oscillation detector 202 of FIG. 1. The oscillation detector 1502 is also configured to detect oscillations at the frequency where the loop gain equals $1\angle 180°$. However, the internal configuration of the oscillation detector 1502 differs from the internal configuration of the oscillation detector 202 shown in FIG. 2.

[0101] In particular, referring to FIG. 15, the oscillation detector 1502 receives the input signal $x(t)$ and the output of the second forward path gain element 118, $\tilde{x}(t)$ and generates a control parameter, P which is output to the adjustable feedback factor, H 210. The control parameter, P indicates whether oscillations due to instability in the feedback loop are present and commands the feedback factor, H 210 to adjust the loop gain if necessary.

[0102] The design of the oscillation detector 1502 leverages an assumption that $\tilde{x}(t)$ may include components which are related to the input signal $x(t)$ (i.e., a magnitude and phase altered version of $x(t)$), an oscillatory signal due to instability, and an active noise cancellation signal. Thus, $\tilde{x}(t)$ can be expressed in the frequency domain as:

$$\tilde{X}(\omega) = \frac{X(\omega)(G_2A_2 + G_1G_2A_1)}{1+G_1G_2HA} + \frac{G_1G_2G_3Z(\omega) - G_1G_2HN(\omega)}{1+G_1G_2HA}$$

[0103] The active noise cancellation signal is assumed to be bandwidth limited to a frequency range which is less than the crossover frequency of the feedback loop (e.g., 1kHz). It is also assumed that the oscillatory signal lies within a frequency range which is greater than the crossover frequency of the feedback loop.

[0104] Based on these assumptions about $\tilde{x}(t)$, the oscillation detector 1502 detects whether an oscillatory signal exists in $\tilde{x}(t)$ by first isolating the oscillatory component of $\tilde{x}(t)$ and then applying a phase-locked-loop 1602 to detect the presence of the oscillatory component.

[0105] One step taken by the oscillation detector 1501 is to isolate the oscillatory component of $\tilde{x}(t)$ is to removes the component of $\tilde{x}(t)$ which is related to the input signal $x(t)$. In general, $x(t)$ cannot simply be subtracted from $\tilde{x}(t)$ since the component of $x(t)$ included in $\tilde{x}(t)$ typically differs from $x(t)$ in both magnitude and phase. As is shown above, the component of $\tilde{x}(t)$ which is related to the input signal $x(t)$ can be expressed in the frequency domain as:

$$\frac{X(\omega)(G_2A_2 + G_1G_2A_1)}{1+G_1G_2HA}$$

[0106] To ensure that the component of $\tilde{x}(t)$ which is related to the input signal $x(t)$ is correctly removed from $\tilde{x}(t)$, a pre-filter 1604 and an adjustable gain factor 1606 are applied to $x(t)$ before $x(t)$ is subtracted from $\tilde{x}(t)$. First, the pre-filter 1604 is applied to $x(t)$. Based on the configuration of the system for active noise reduction 1500 shown in FIG. 14, the pre-filter 1604 has a transfer function of:

$$G_2A_2 + G_1G_2A_1$$

[0107] The result of applying the pre-filter 1604 to $x(t)$ is then passed to the adjustable gain factor 1606. Based on the configuration of the system for active noise reduction 1500 shown in FIG. 14, the adjustable gain factor 1606 has a transfer function of:

$$\frac{1}{1+G_1G_2HA}$$

[0108] The result of applying the adjustable gain factor 1606 to the output of the pre-filter 1604 is then passed to an adder 1608 where it is subtracted from $\tilde{x}(t)$, resulting in a version of $\tilde{x}(t)$ with the component related to the input signal $x(t)$ removed.

[0109] The output of the adder 1608 is passed to a high pass filter 1610 which removes the component of $\tilde{x}(t)$ which is related to the active noise cancellation signal. The result of the high pass filter 1610 is the isolated oscillatory component of $\tilde{x}(t)$. The result of the high pass filter 1610 is passed to a conventional phase locked loop 1602 with a carrier detect output. Such a phase locked loop 1602 can be implemented in software or in hardware (e.g., a LMC568 amplitude-linear phase-locked loop).

[0110] The detect output of the phase locked loop 1602 indicates whether an amplitude detector 1614 in the phase locked loop 1602 detected a signal with an above-threshold amplitude at the VCO 1613 frequency. In some examples, the output of the phase locked loop 1602 is high (i.e., True or 1) if an oscillatory component is detected and low (i.e., False or 0) if an oscillatory component is not detected. In some embodiments, the PLL 1602 is a National Semiconductor LMC568.

[0111] The output of the phase locked loop 1602 is passed to a gain controller 1616 which determines whether the adjustable gain factor 1606 and adjustable feedback factor, H (FIG. 2, element 210) are adjusted to modify the bandwidth of the feedback loop gain. In some examples, the gain controller 1616 also determines by how much the adjustable gain factor 1606 and the adjustable feedback factor 210 are adjusted. The adjustable gain factor 1606 is adjusted based on the output of the gain controller 1616. The output of the gain controller 1616, P, is also passed out of the oscillation detector 1502 to the adjustable feedback factor 210 where it is used by the adjustable feedback factor 210 to modify the bandwidth of the feedback loop gain.

[0112] Referring to FIG. 16, one embodiment of the gain controller 1616 is configured to accept the output of the phase locked loop 1602 and to use the output of the phase locked loop 1602 to determine whether to adjust the gain of the adjustable gain factor 1606 and the adjustable feedback factor 210, and if so, in which direction (i.e., a positive or negative adjustment).

[0113] In particular, if the output of the phase locked loop 1602 indicates that an oscillatory signal is present, the gain controller 1616 generates a value for P which causes the adjustable feedback factor 210 to reduce the loop gain by X dB. P is also used to adjust the adjustable gain factor 1606 to ensure that the correct scaling is applied to $x(t)$ before it is subtracted from $\tilde{x}(t)$. In some examples, X is equal to 3dB.

[0114] If the phase locked loop 1602 indicates that no oscillatory signal is present, the gain controller 1616 waits for a predetermined amount of time, T_D, and then generates a value for P which causes the adjustable feedback factor 210 to increase the loop gain by K dB. P is also used to adjust the adjustable gain factor 1606 to ensure that the correct scaling is applied to $x(t)$ before it is subtracted from $\tilde{x}(t)$. In some examples, K is equal to 3dB.

[0115] In some examples, the value of X is greater than the value of K which causes the reduction of the loop gain when oscillation is detected to be greater than the increase in loop gain when no oscillation is detected. This may result in a rapid reduction of the detected oscillation. For example, if the value of X is 9dB, the loop gain is drastically reduced when an oscillation is detected. If the value of K is 1dB, the loop gain will then slowly increase until a gain margin level less than the gain before instability was detected is reached.

6.3 Alternative Embodiment #2

[0116] Referring to FIG. 17, another embodiment of a system for acoustic active noise reduction 1700 is configured in much the same way as the system for acoustic active noise reduction 1500 of FIG. 14 with the exception that the $\tilde{x}(t)$ signal is taken from the output of the adjustable feedback factor 210. Thus, $\tilde{x}(t)$ can be expressed in the frequency domain as:

$$\tilde{X}(\omega)=\frac{X(\omega)(G_2HAA_2+G_1G_2HAA_1)}{1+G_1G_2HA}+\frac{G_1G_2G_3HAZ(\omega)-HN(\omega)}{1+G_1G_2HA}$$

[0117] Due to the slightly different configuration of the system 1700 of FIG. 17, the pre-filter (FIG. 15, element 1604) included in the oscillation detector 1702 and the adjustable gain factor (FIG. 15, element 1606) included in the oscillation detector 1702 are adjusted to ensure that the component of $\tilde{x}(t)$ which is related to the input signal $x(t)$ is correctly removed from $\tilde{x}(t)$. The component of $\tilde{x}(t)$ which is related to the input signal $x(t)$ can be expressed in the frequency domain as:

$$\frac{X(\omega)(G_2HAA_2 + G_1G_2HAA_1)}{1 + G_1G_2HA}$$

[0118] Thus, the pre-filter (FIG. 15, element 1604) has a transfer function of:

$$G_2HAA_2 + G_1G_2HAA_1$$

and the adjustable gain factor (FIG. 15, element 1606) has a transfer function of:

$$\frac{1}{1 + G_1G_2HA}$$

[0119] The remainder of the system 1700 operates in much the same way as the system of FIG. 14.

6.4 Alternative Oscillation/Blocked Tip Detector

[0120] Referring to FIG. 18, another embodiment of an oscillation/blocked tip detector 1810 is configured similarly to the oscillation/blocked tip detector 1110 shown in FIG. 11. A feature of the oscillation/blocked tip detector 1810 is that the embodiment illustrated in FIG. 18 includes an oscillation detector 1802 which is configured to use a phase locked loop detect oscillatory signals in $\tilde{x}(t)$ (i.e., as in the oscillation detector 1502 illustrated in FIG. 15). Note that the oscillation detector 1802 is slightly different from the oscillation detector 1502 illustrated in FIG. 15 in that it outputs a parameter representative of a Boolean value (i.e., True/False or 0/1) indicating whether to reduce the loop gain.

6.5 Other Alternatives

[0121] The above description focuses on a single channel of an in-ear headphone system. However, it is noted that the system described above can be extended to two or more channels.

[0122] Just as the oscillation detector can be used to detect instability without the use of the blocked tip detector, the blocked tip detector can be used alone to detect a potential instability without the use of the oscillation detector. Neither depends on the other and each can be effectively used independently.

[0123] Although described in the context of an in-ear active noise cancellation system, the approaches described above can be applied in other situations. For example, the approaches can be applied to over-the-ear noise cancellation headphones. More generally, the approaches may be applied to other audio feedback situations, particularly when characteristics of an audio component of a feedback path may vary, for example the audio characteristics of a room or a vehicle passenger compartment may change (e.g., when a door or window is opened). Furthermore, the method of oscillation and impedance detection described above may be applied to motion control systems where feedback loop oscillation and mechanical impedance (e.g., velocity/force) can be detected and measured.

[0124] In the above description, the feedback loop gain is adjusted by modifying a feedback factor in the feedback path. In some examples, instead of adjusting the feedback loop gain in the feedback path, the forward path gain elements can be adjusted.

[0125] In some examples, the circuitry to implement the approaches described above is integrated into a housing including the drivers and microphones. In other examples, the circuitry is provided separately, and may be configurable to be suitable for different housings and arrangements of drivers and microphones.

[0126] In some examples, in active noise reduction systems which include feedback, feedforward, and audio input filtering, it is desirable to modify the filter transfer functions of all three of the filters (i.e., the audio input filter, the feedforward filter, and the feedback filter) concurrently when the instability/oscillation detector is activated. Modifying the transfer function of all three filters concurrently compensates for the entire system response due to a change in the feedback loop gain response. Such a modification of filter transfer functions can occur in both analog hardware or DSP based systems.

[0127] In some examples, a microcontroller can be used to interpret the outputs of one or more of the oscillation detector, blocked tip detector, and outside pressure level detector and take action to reduce the loop gain.

[0128] In some examples, a dedicated digital signal processor or microcontroller performs the band-pass filtering, peak detection, comparator function, and gain reduction function.

[0129] In some examples, the input signal is muted when the bandwidth of the feedback loop is being adjusted.

[0130] It is to be understood that the foregoing description is intended to illustrate and not to limit the scope of the invention, which is defined by the scope of the appended claims. Other embodiments are within the scope of the following claims.

What is claimed is:

1. A feedback based active noise reduction system comprising:

a feedback component for forming at least part of a feedback loop having an audio path segment, the feedback component including

a first signal input for accepting an input signal,

a driver output for providing a driver signal to a driver of the audio path segment,

a first feedback input for accepting a first feedback signal from a first sensor responsive to a signal on the audio path segment,

a control input for accepting a control parameter for adjusting at least one of a gain characteristic and a phase characteristic of the feedback loop, and

an instability detector for detecting an instability condition in the feedback component and forming the control parameter based on a result of the detection, the instability detector including

a feedback loop signal input for accepting a feedback loop signal,

a circuit for detecting an oscillatory signal component in the feedback loop signal not represented in the input signal, and

a control parameter output for providing the control parameter to the control parameter input of the feedback element.

2. The system of claim 1 wherein the feedback loop signal represents the driver signal.

3. The system of claim 1 wherein the feedback loop signal represents the first feedback signal.

4. The system of claim 1 wherein the circuit for detecting the oscillatory signal component in the feedback loop signal includes,

a circuit for forming a modified feedback loop signal, the circuit including circuitry for removing a component of the input signal from the feedback loop signal, and

a circuit for detecting the oscillatory signal component in a specified frequency range in the modified feedback loop signal.

5. The system of claim 4 wherein the circuit for detecting the oscillatory signal component includes a voltage controlled oscillator and a circuit for combining an output of the voltage controlled oscillator and the modified feedback loop signal.

6. The system of claim 1 wherein the feedback component further includes a feed-forward input for accepting a first feed-forward signal from a second sensor responsive to a second signal on the audio path segment.

7. The system of claim 4 wherein the circuit for detecting the oscillatory signal component in the feedback loop signal further includes a high-pass filter for removing an active noise reduction signal component from the feedback loop signal.

8. The system of claim 4 wherein the circuit for forming the modified feedback loop signal includes,

a filtering element for forming the component of the input signal, and

a signal combiner for removing the component of the input signal from the feedback loop signal.

9. The system of claim 8 wherein the filtering element includes a control parameter input for accepting the control parameter for adjusting a gain and phase characteristic of the filtering element.

10. The system of claim 1 wherein the circuit for detecting the oscillatory signal includes a phase locked loop (PLL).

11. A method for feedback based active noise reduction comprising:

accepting, at a first signal input of a feedback component, an input signal, the feedback component forming at least part of a feedback loop having an audio path segment;

providing, through a driver output of the feedback component, a driver signal to a driver of the audio path segment;

accepting, at a first feedback input of the feedback component, a first feedback signal from a first sensor responsive to a signal on the audio path segment;

accepting, at a control input of the feedback component, a control parameter for adjusting at least one of a gain characteristic and a phase characteristic of the feedback loop; and

detecting an instability condition in the feedback component and forming the control parameter based on a result of the detection, detecting the instability condition including

accepting, at a feedback loop signal input, a feedback loop signal,

detecting an oscillatory signal component in the feedback loop signal, the oscillatory signal component not represented in the input signal, and

providing, through a control parameter output, the control parameter to the control parameter input of the feedback element.

12. The method of claim 11 wherein the feedback loop signal represents the driver signal.

13. The method of claim 11 wherein the feedback loop signal represents the first feedback signal.

14. The method of claim 11 wherein detecting the oscillatory signal component in the feedback loop signal includes,

forming a modified feedback loop signal, including removing a component of the input signal from the feedback loop signal, and

detecting the oscillatory signal component in a specified frequency range in the modified feedback loop signal.

15. The method of claim 14 wherein detecting the oscillatory signal component includes combining an output of a voltage controlled oscillator and the modified feedback loop signal.

16. The method of claim 11 wherein further comprising accepting, at a feed-forward input, a first feed-forward signal from a second sensor responsive to a second signal on the audio path segment.

17. The method of claim 14 wherein detecting the oscillatory signal component in the feedback loop signal further includes applying a high-pass filter to the feedback loop signal for removing an active noise reduction signal component from the feedback loop signal.

18. The method of claim 14 wherein forming the modified feedback loop signal includes,

forming the component of the input signal at a filtering element; and

removing the component of the input signal from the feedback loop signal at a signal combiner.

19. The method of claim 18 wherein forming the component of the input signal at the filtering element includes accepting, at a control parameter input of the filtering element, the control parameter for adjusting a gain and phase characteristic of the filtering element.

20. The method of claim 11 wherein detecting the oscillatory signal includes using a phase locked loop (PLL) for detecting and tracking the oscillatory signal.

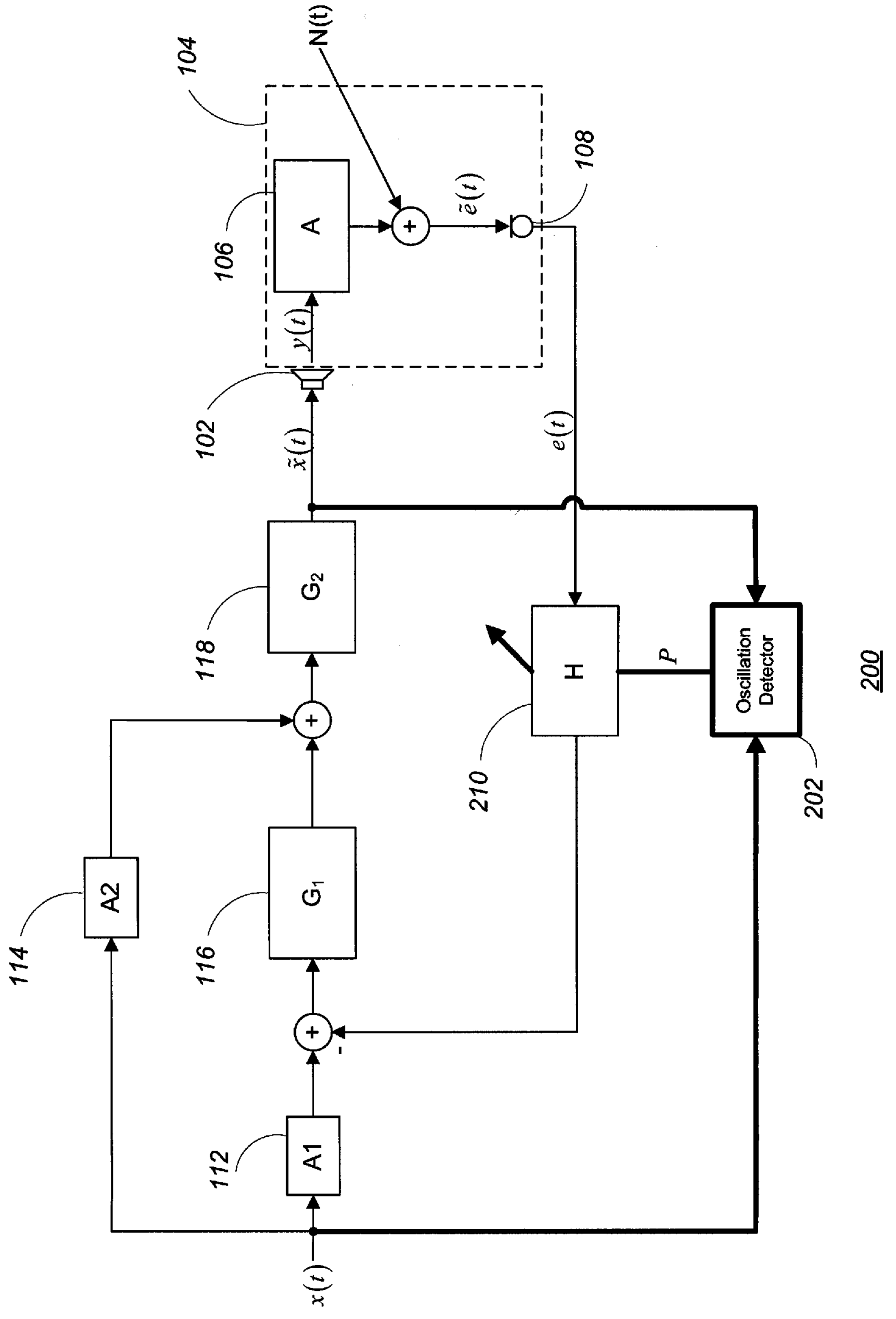

104
N(t)
106
A
+
$\tilde{e}(t)$
108
$y(t)$
102
$\tilde{x}(t)$
$e(t)$
118
G_2
H
P
Oscillation Detector
200
210
202
114
A2
+
116
G_1
+
-
112
A1
$x(t)$

FIG. 1

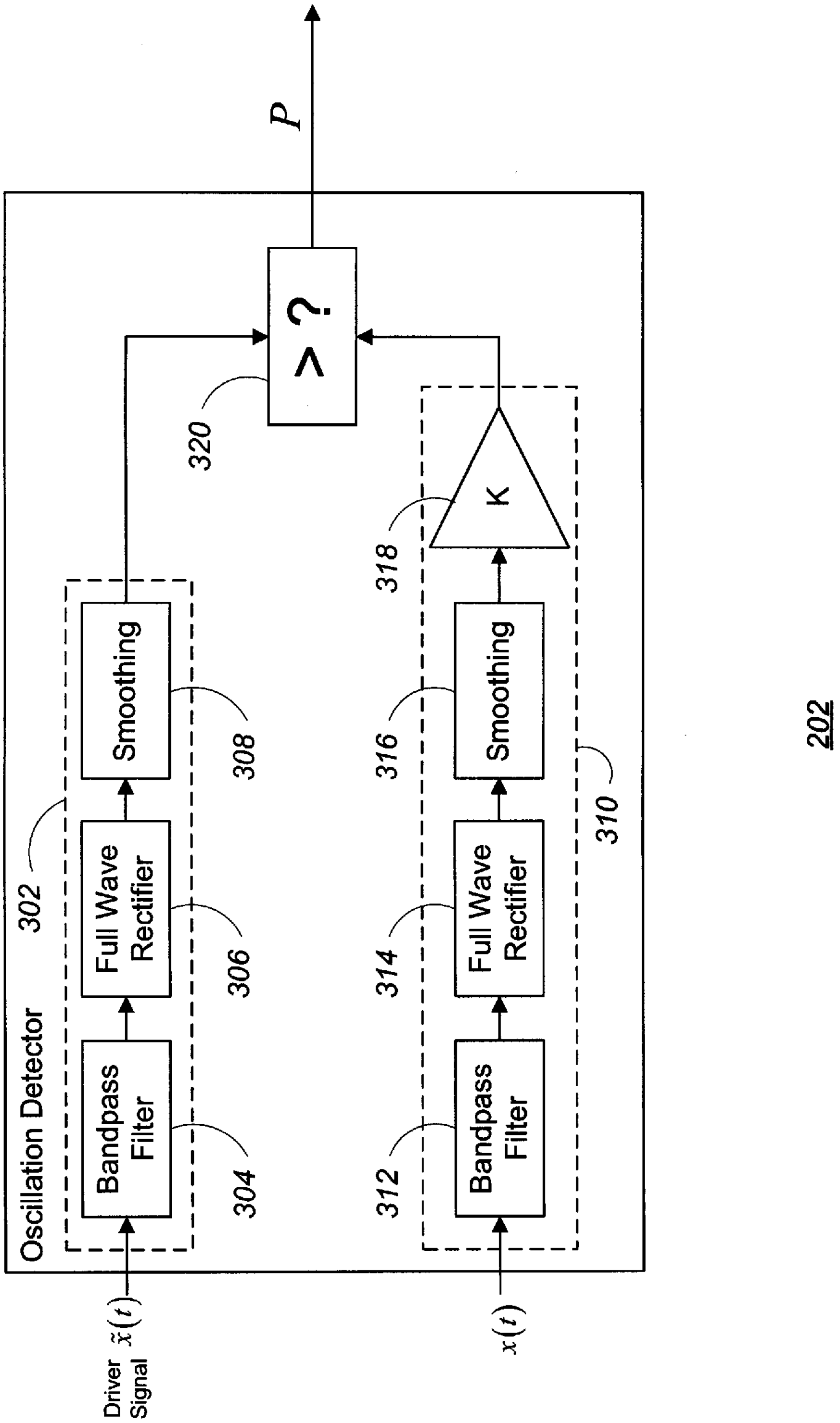

Oscillation Detector
Driver Signal
$\tilde{x}(t)$
Bandpass Filter
Full Wave Rectifier
Smoothing
302
304
306
308
$x(t)$
Bandpass Filter
Full Wave Rectifier
Smoothing
K
310
312
314
316
318
> ?
320
P
202

FIG. 2

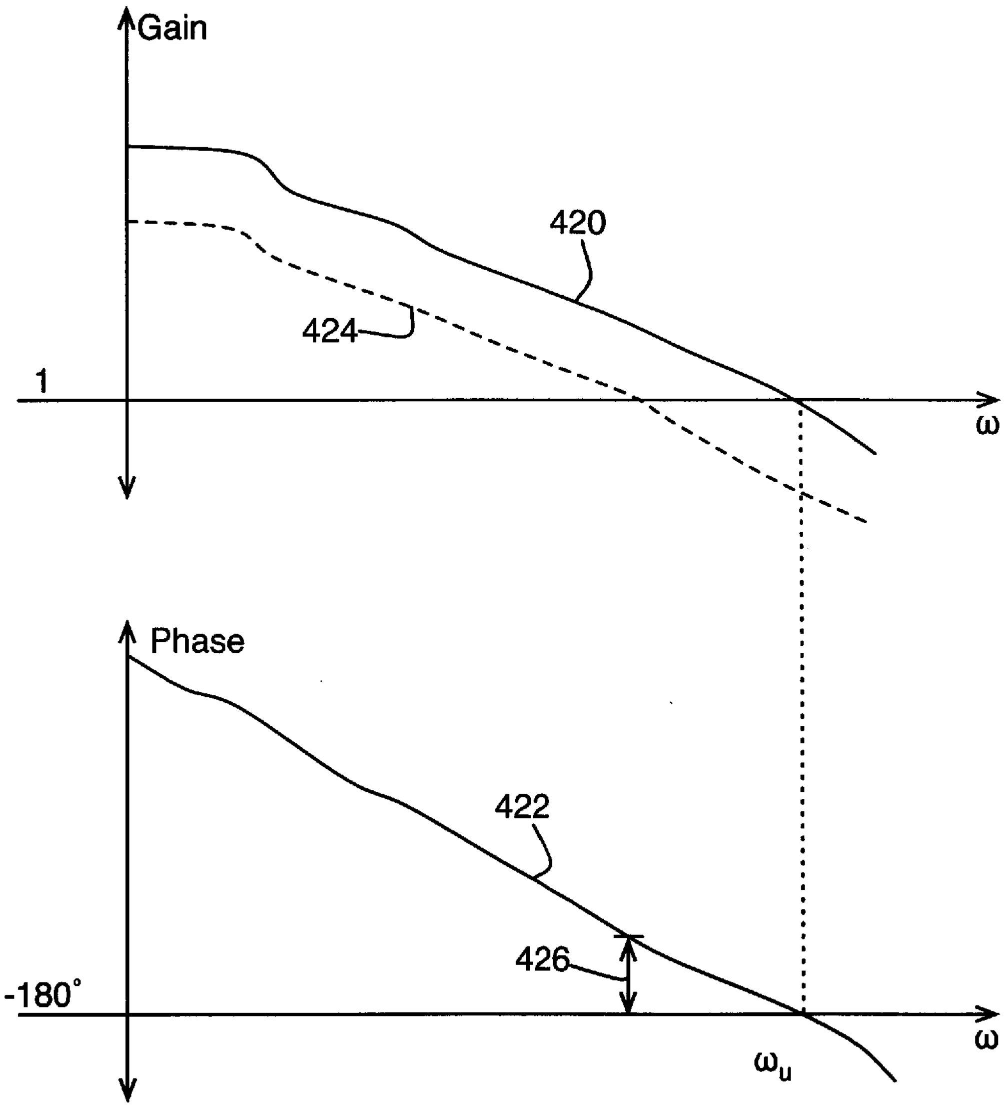


FIG. 3

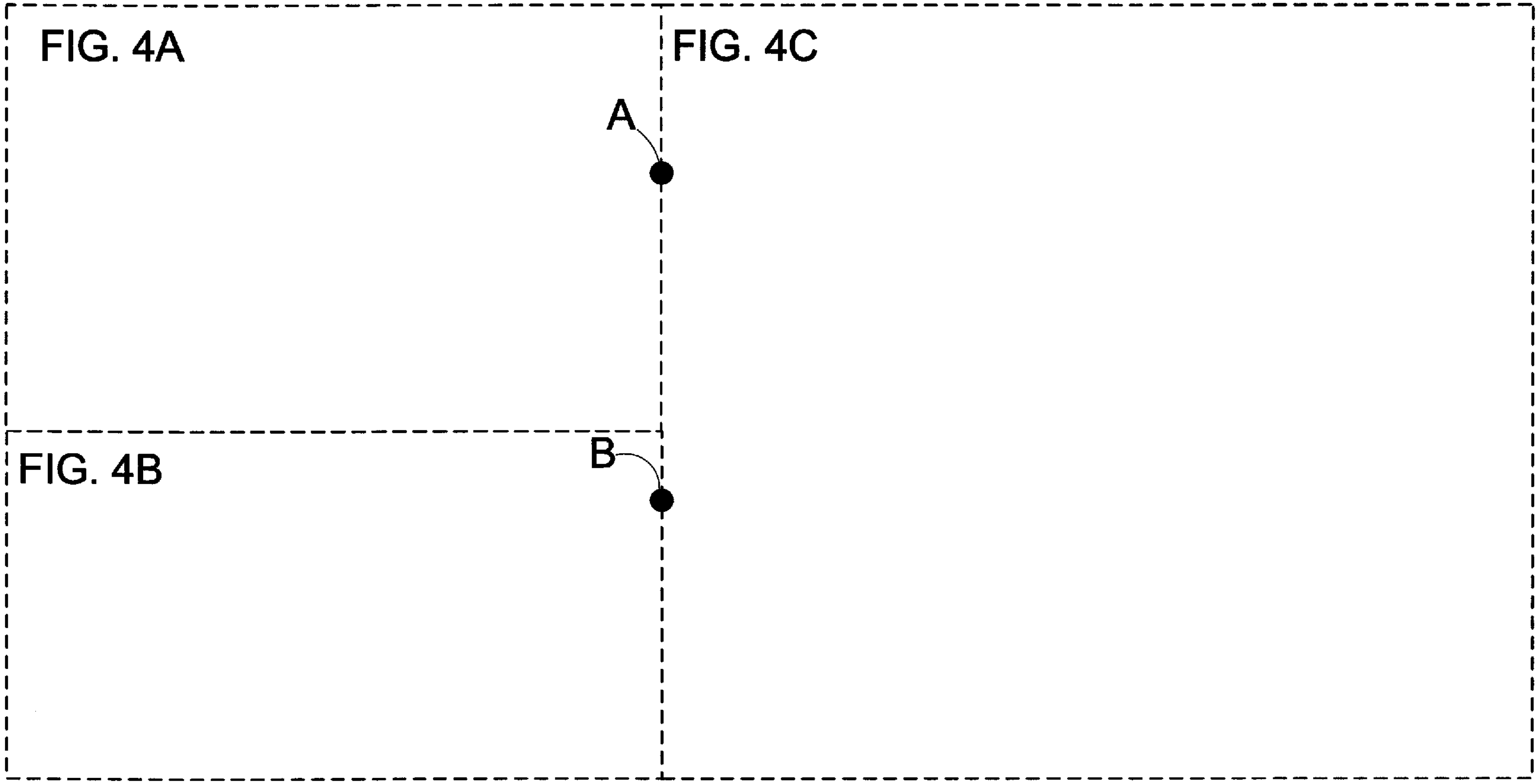


FIG. 4

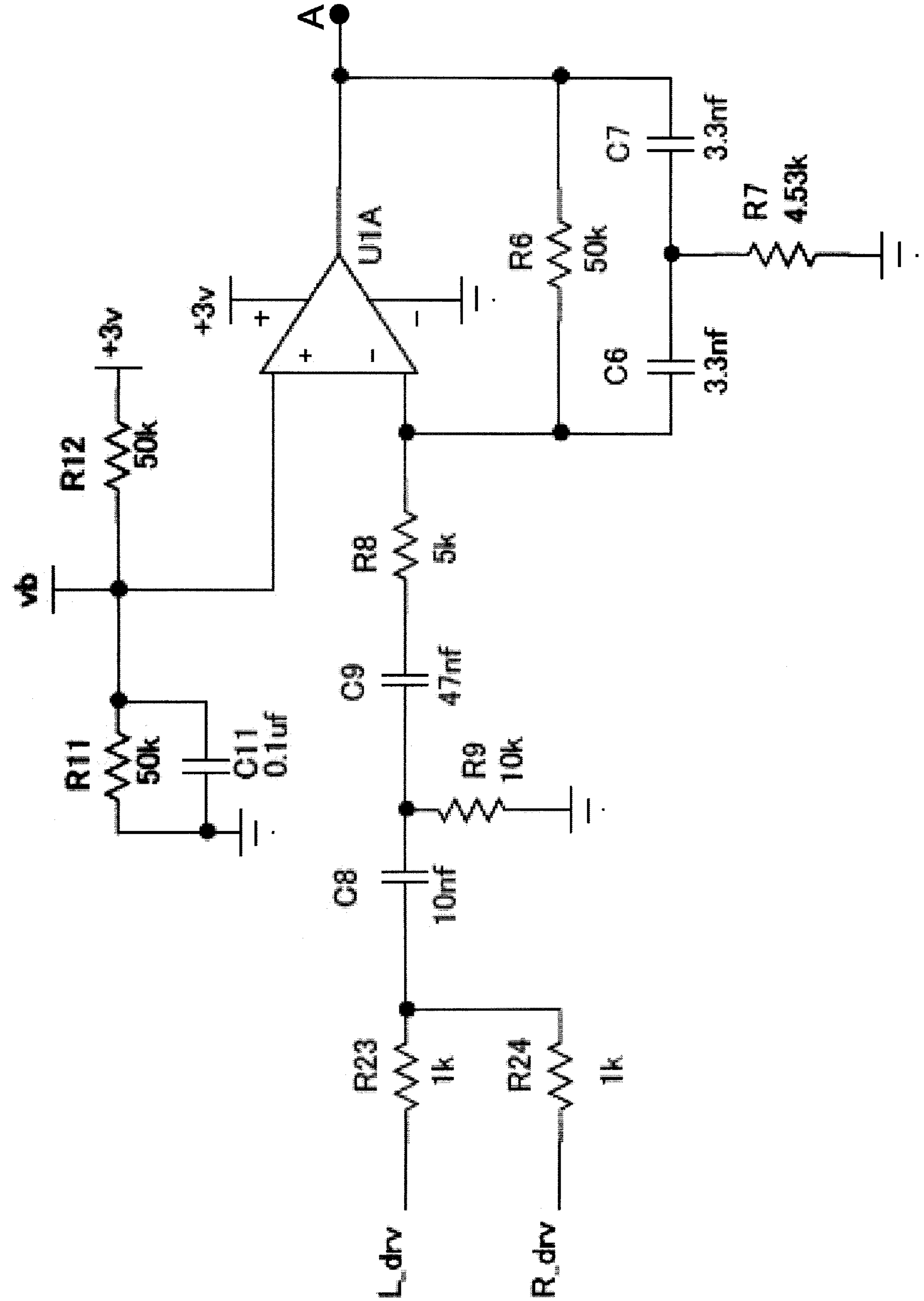

A
U1A
+3v
+
-
+
-
R6
50k
C7
3.3nf
R7
4.53k
C6
3.3nf
R12
50k
+3v
vb
R8
5k
C9
47nf
R11
50k
C11
0.1uf
R9
10k
C8
10nf
R23
1k
R24
1k
L_drv
R_drv

FIG. 4A

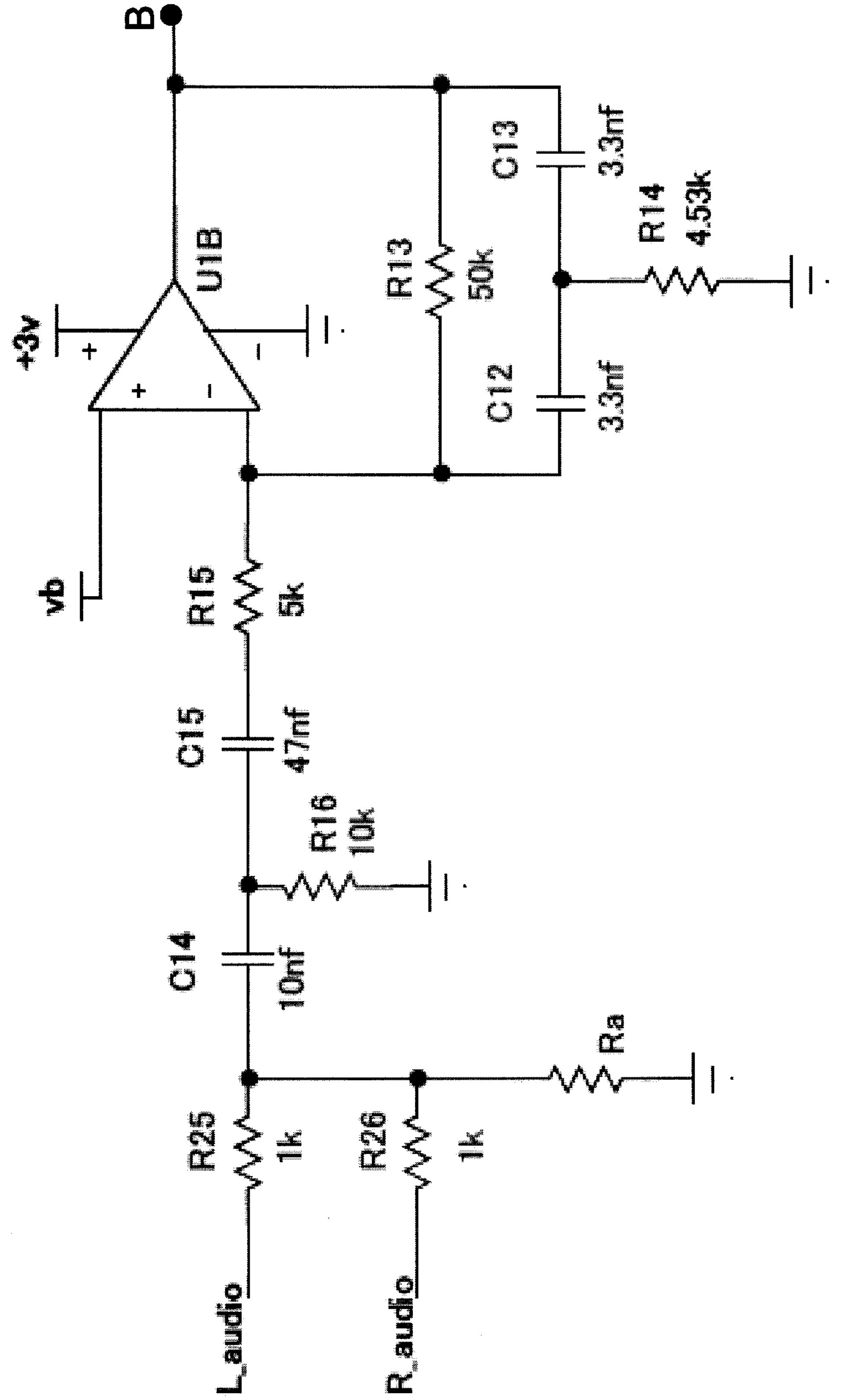

B
U1B
+3v
+
-
+
-
vb
R13
50k
C13
3.3nf
R14
4.53k
C12
3.3nf
R15
5k
C15
47nf
R16
10k
C14
10nf
Ra
R25
1k
R26
1k
L_audio
R_audio

FIG. 4B

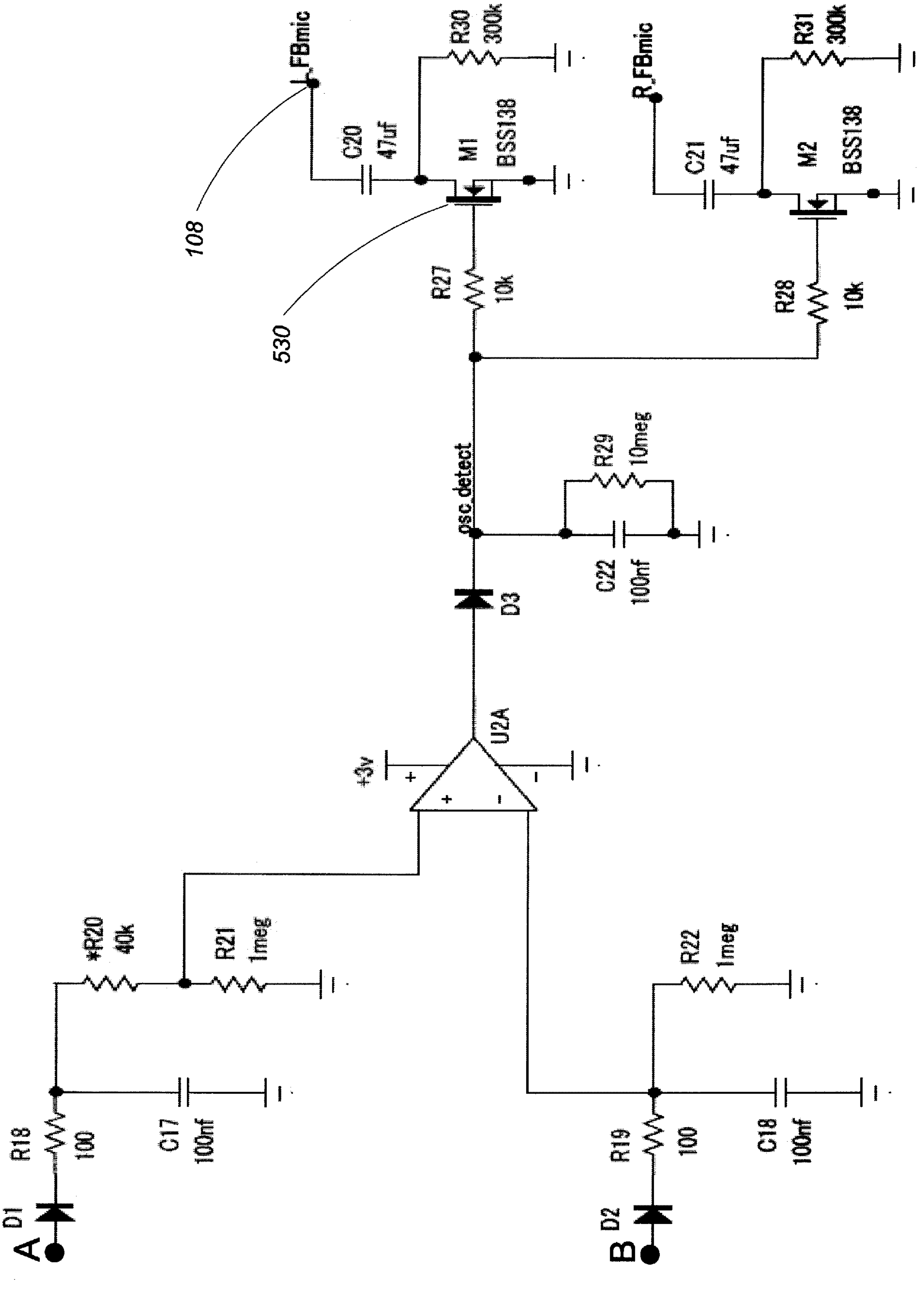

A
D1
R18
100
C17
100nf
*R20
40k
R21
1meg
B
D2
R19
100
C18
100nf
R22
1meg
+3v
+
-
U2A
D3
osc detect
C22
100nf
R29
10meg
R27
10k
R28
10k
530
108
FBmic
C20
47uf
M1
BSS138
R30
300k
R_FBmic
C21
47uf
M2
BSS138
R31
300k

FIG. 4C

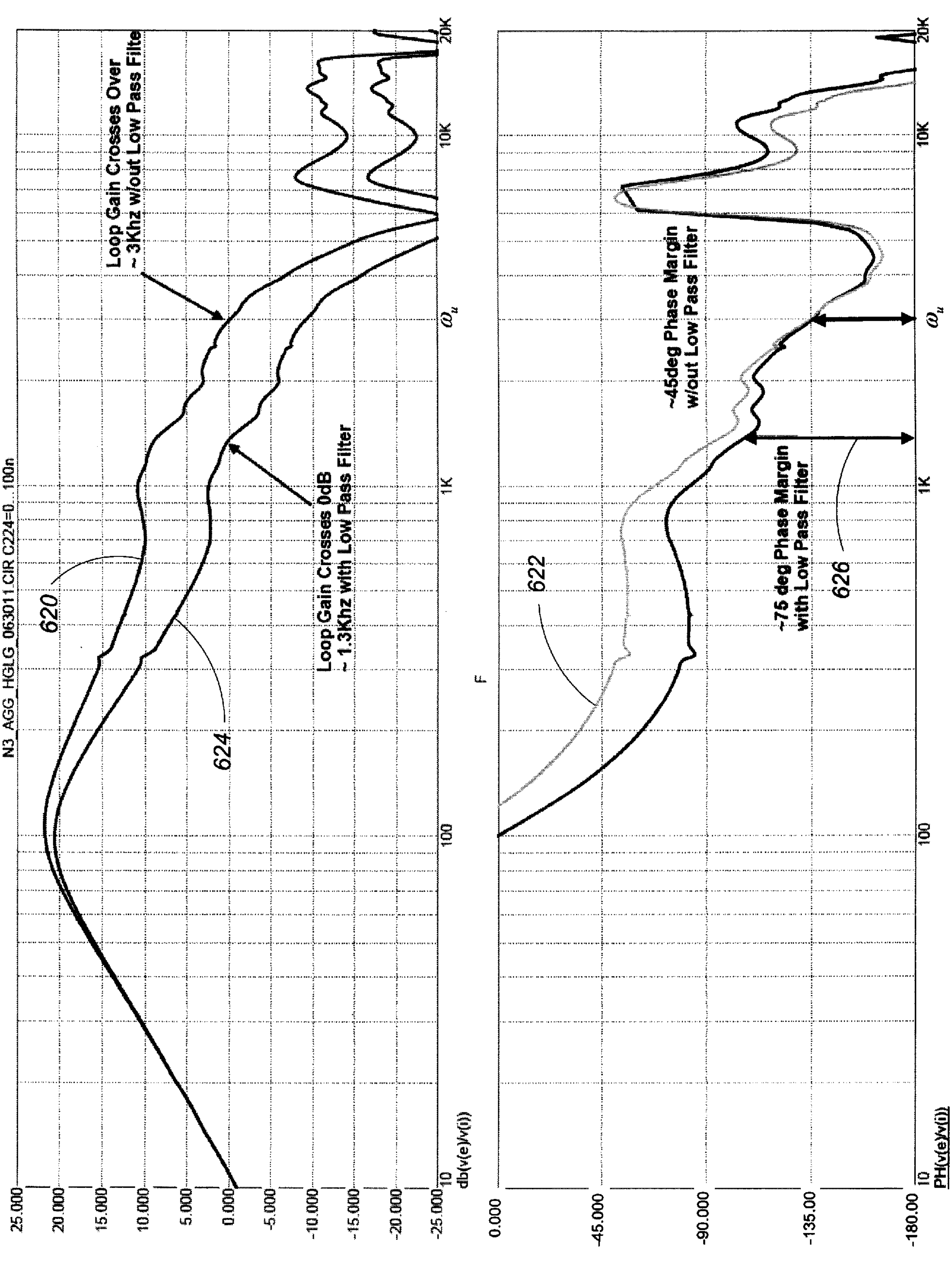

N3_AGG_HGLG_063011.CIR C224=0...100n
25.000
20.000
15.000
10.000
5.000
0.000
-5.000
-10.000
-15.000
-20.000
-25.000
db(v(e)/v(i))
10
100
1K
10K
20K
F
ωu
620
624
Loop Gain Crosses Over
~ 3Khz w/out Low Pass Filte
Loop Gain Crosses 0dB
~ 1.3Khz with Low Pass Filter
0.000
-45.000
-90.000
-135.00
-180.00
PH(v(e)/v(i))
622
626
~45deg Phase Margin
w/out Low Pass Filter
~75 deg Phase Margin
with Low Pass Filter

FIG. 5

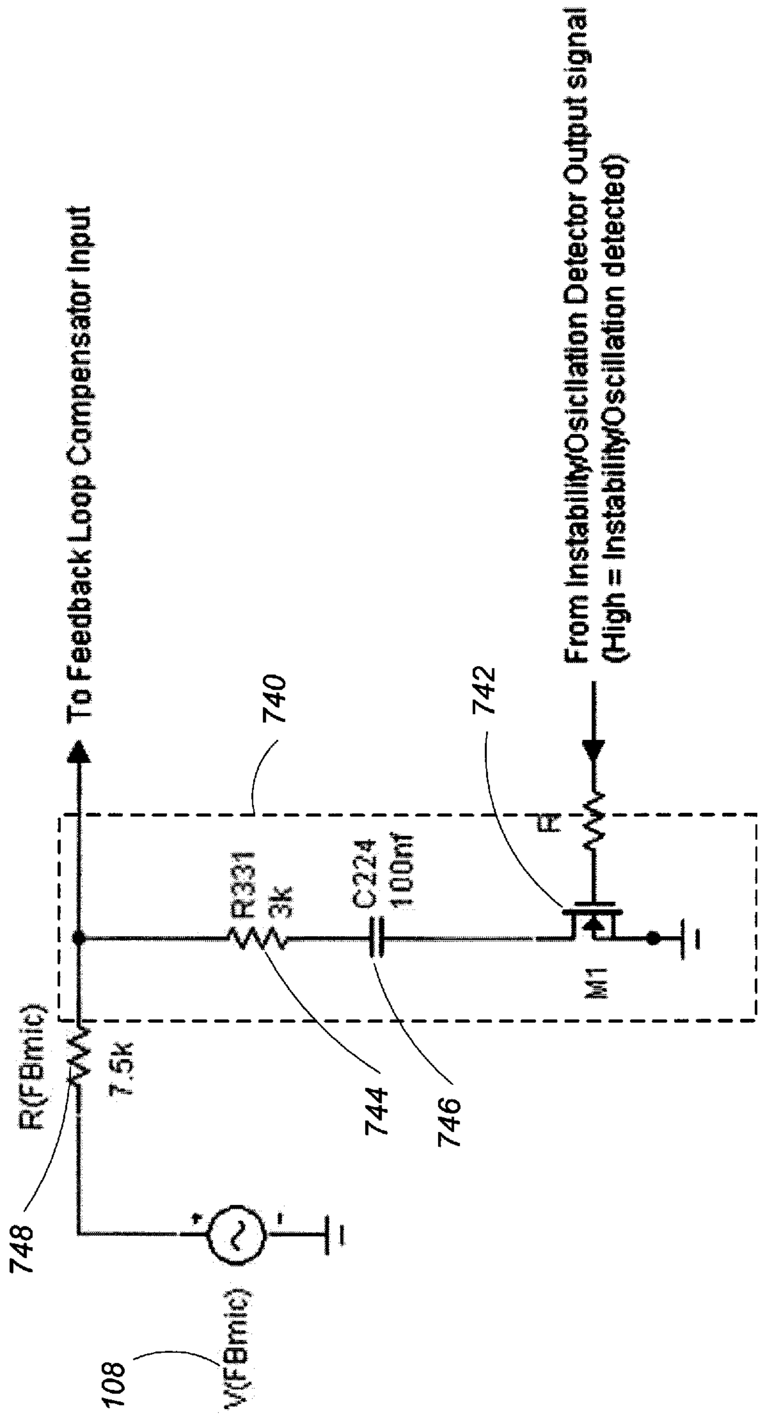

To Feedback Loop Compensator Input
740
742
From Instability/Osicllation Detector Output signal
(High = Instability/Oscillation detected)
R
R331
3k
C224
100nf
M1
R(FBmic)
7.5k
748
744
746
108
V(FBmic)
+
-

FIG. 6

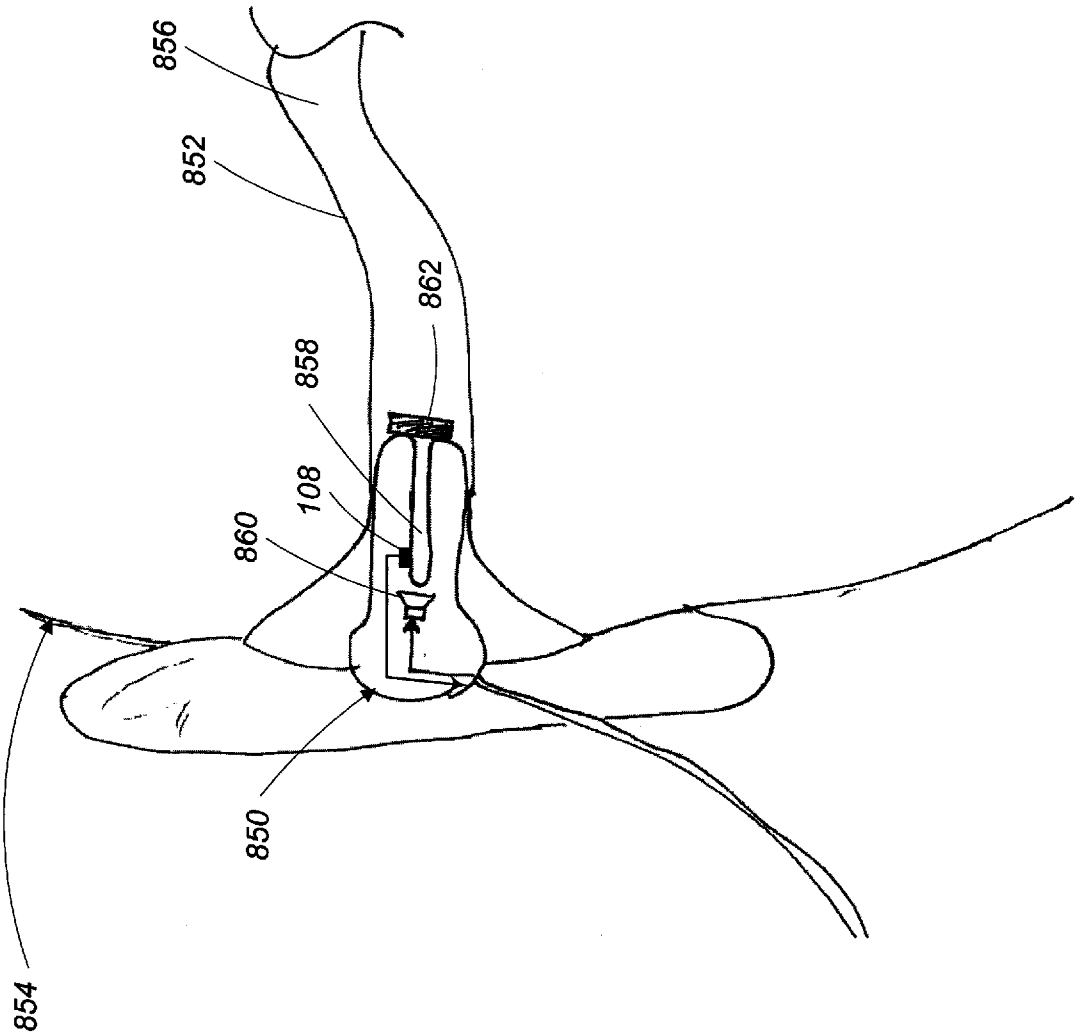


FIG. 7

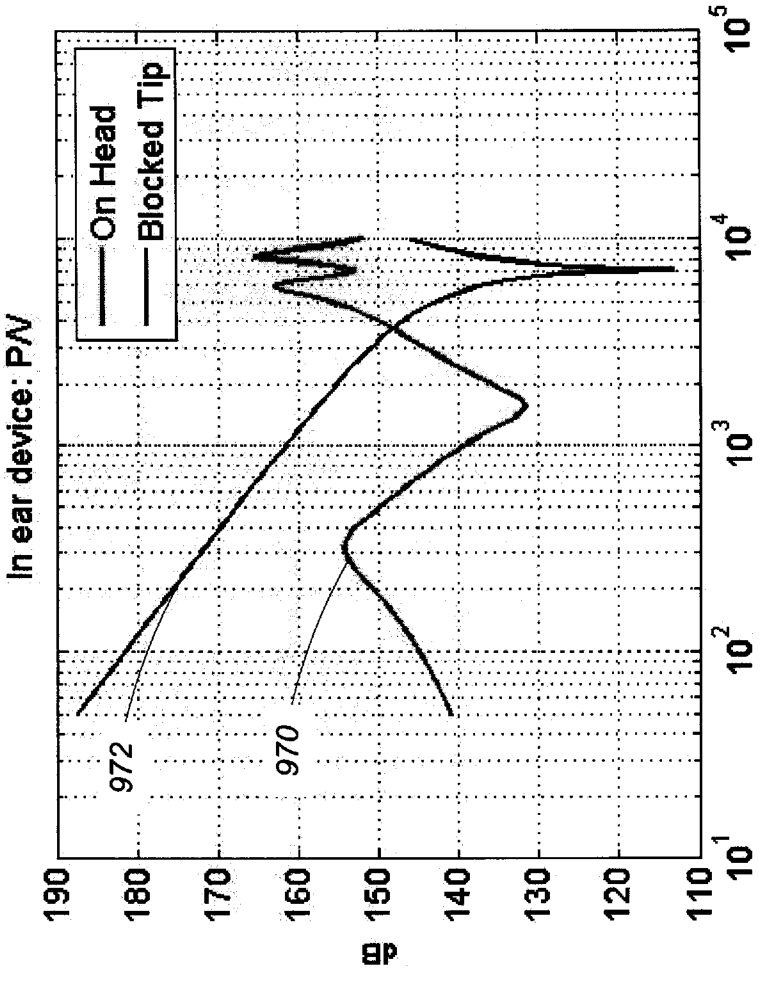

In ear device: P/V
On Head
Blocked Tip
dB
190
180
170
160
150
140
130
120
110
10^1
10^2
10^3
10^4
10^5
Frequency (hertz)
972
970

FIG. 8

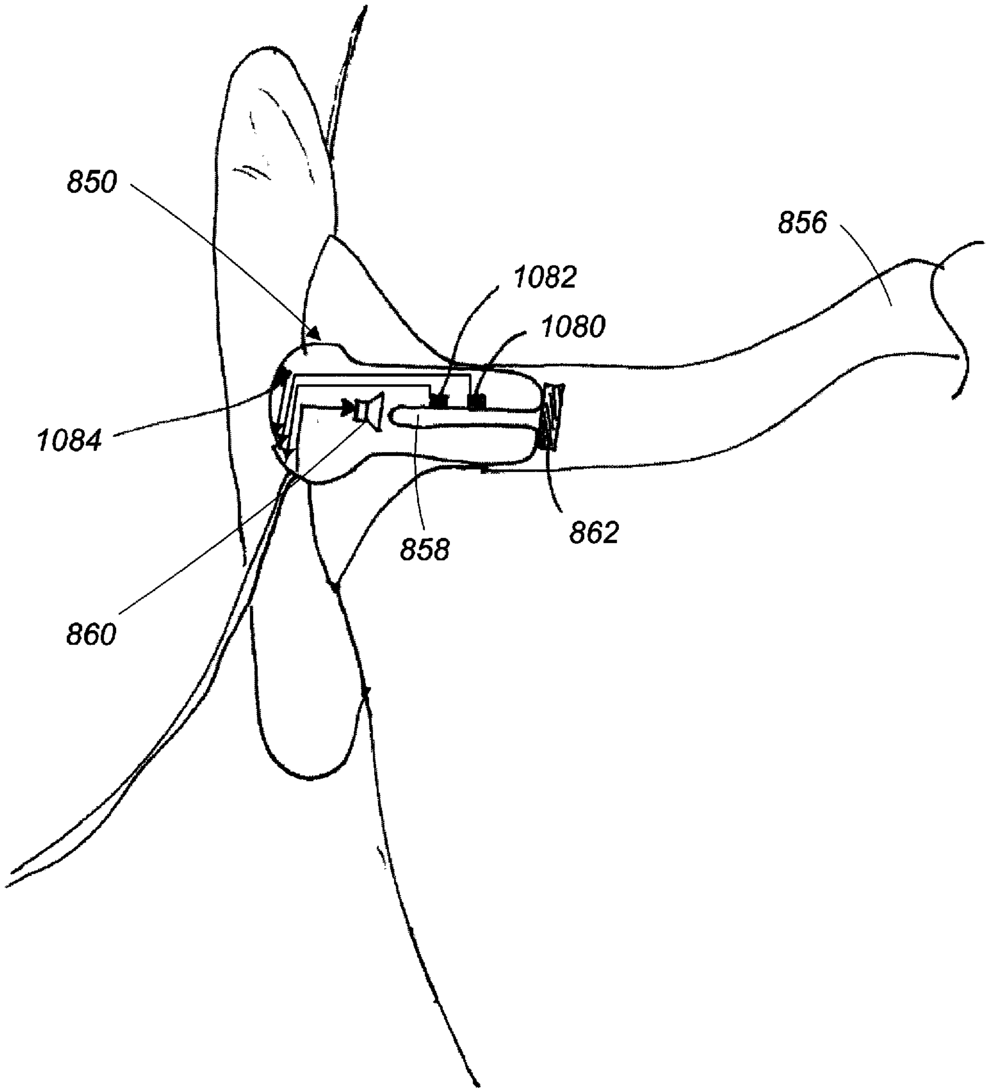


FIG. 9

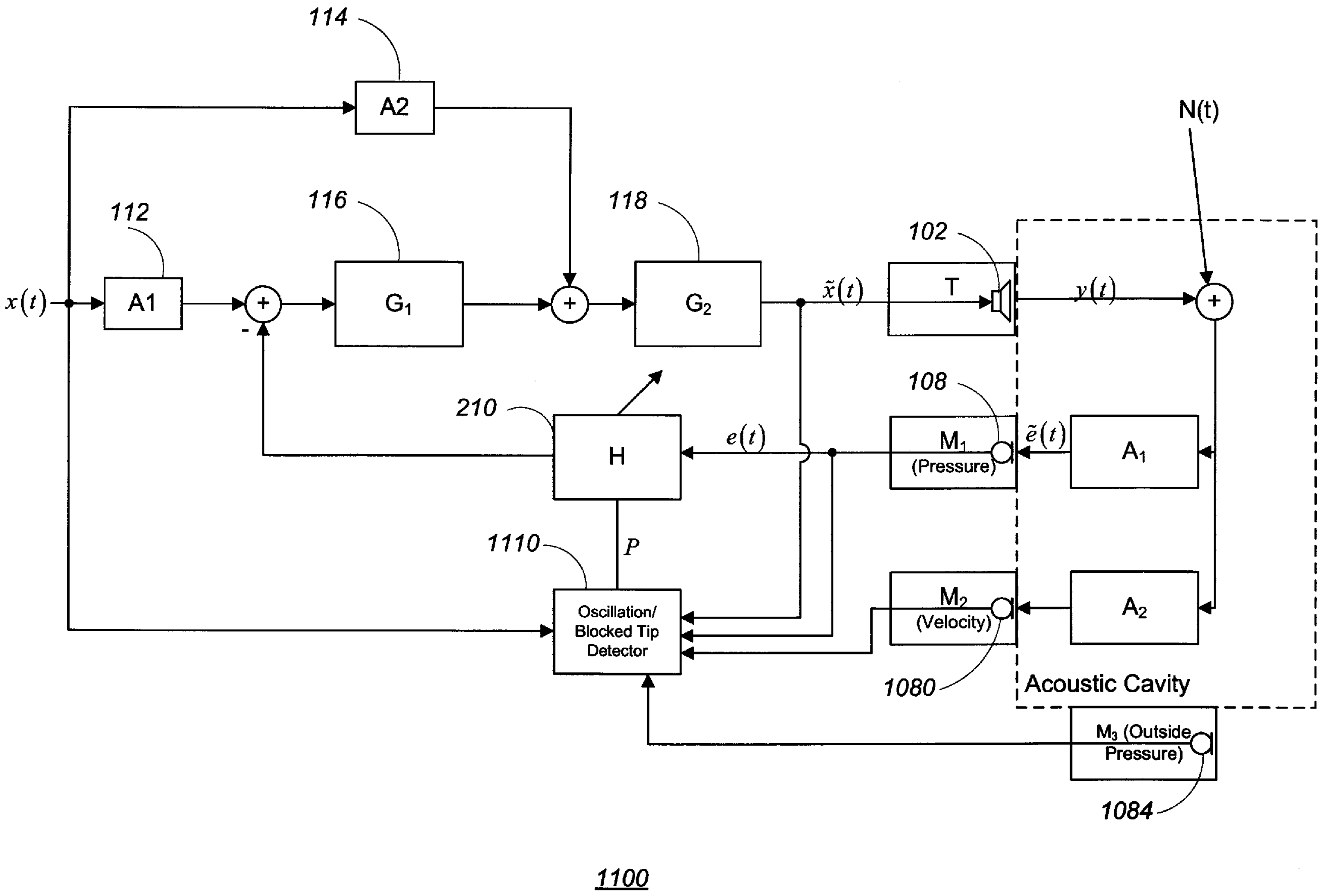
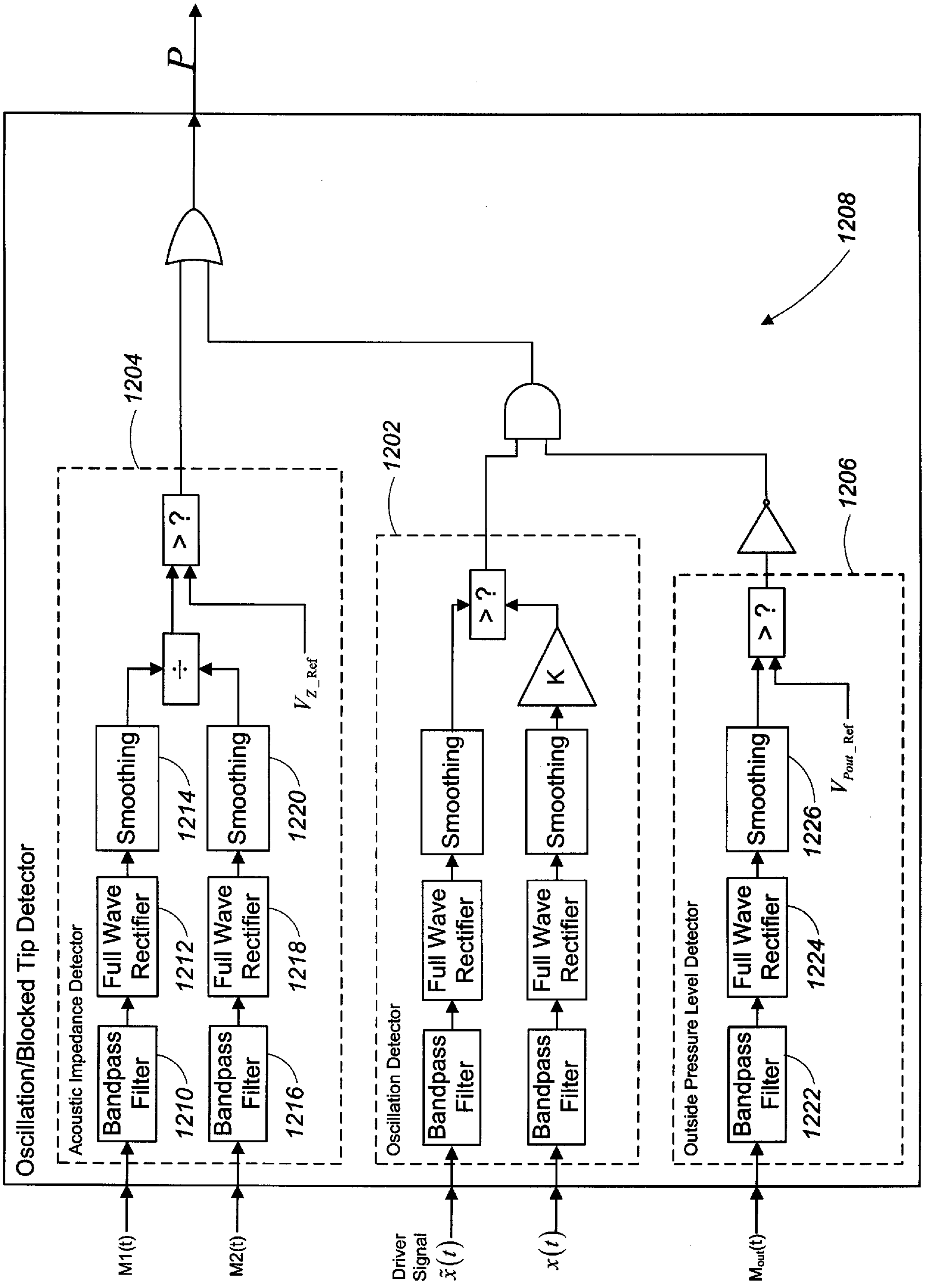

114
A2
112
116
118
102
N(t)
$x(t)$
A1
+
-
G_1
+
G_2
$\tilde{x}(t)$
T
$y(t)$
+
108
210
H
$e(t)$
M_1
(Pressure)
$\tilde{e}(t)$
A_1
1110
P
Oscillation/
Blocked Tip
Detector
M_2
(Velocity)
A_2
1080
Acoustic Cavity
M_3 (Outside
Pressure)
1084
1100

FIG. 10


Oscillation/Blocked Tip Detector
Acoustic Impedance Detector
Oscillation Detector
Outside Pressure Level Detector
M1(t)
M2(t)
Driver Signal $\tilde{x}(t)$
$x(t)$
$M_{out}(t)$
Bandpass Filter
1210
Full Wave Rectifier
1212
Smoothing
1214
Bandpass Filter
1216
Full Wave Rectifier
1218
Smoothing
1220
÷
> ?
V_{Z_Ref}
1204
Bandpass Filter
Full Wave Rectifier
Smoothing
Bandpass Filter
Full Wave Rectifier
Smoothing
K
> ?
1202
Bandpass Filter
1222
Full Wave Rectifier
1224
Smoothing
1226
> ?
V_{Pout_Ref}
1206
1208
P

1110

FIG. 11

Blocked Tip Detector State Table

PD	OD	ZD	BT	CASE
0	0	0	0	STABLE
0	0	1	X	DON'T CARE
0	1	1	X	DON'T CARE
0	1	0	1	UNSTABLE
1	1	0	0	STABLE (FALSE TRIGGER DUE TO OCCLUSION)
1	1	1	1	UNSTABLE
1	0	1	1	UNSTABLE
1	0	0	0	STABLE

BT = Blocked Tip / Instability Detected, Active High

BT = ZD + (/PD)(OD)

FIG. 12

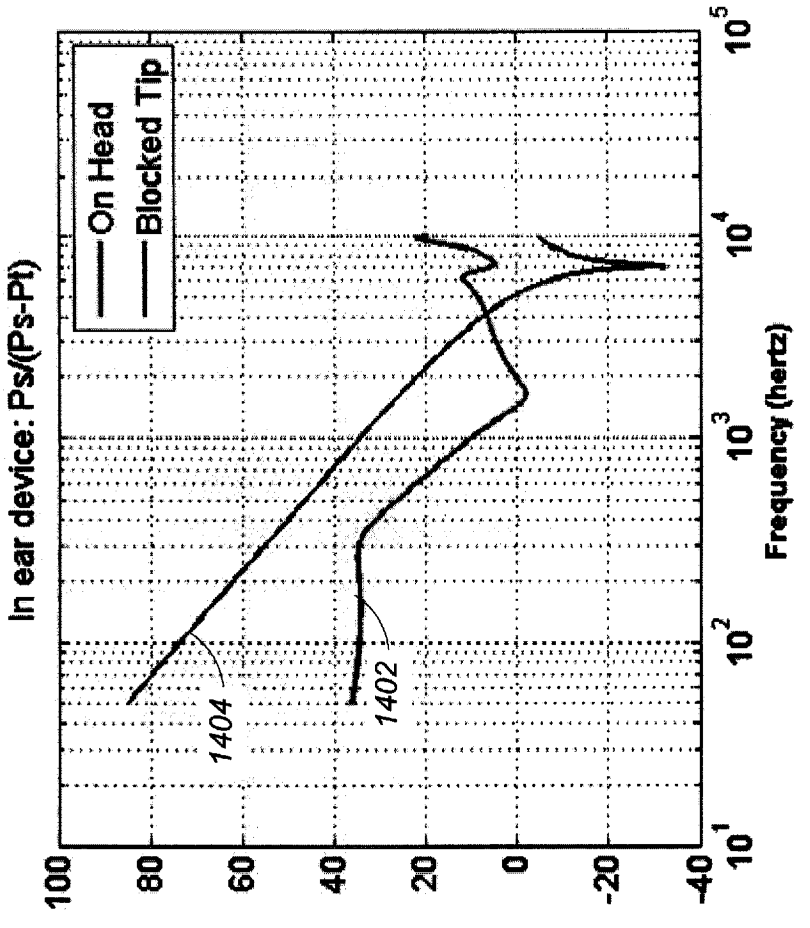

In ear device: Ps/(Ps-Pt)
On Head
Blocked Tip
1404
1402
100
80
60
40
20
0
-20
-40
10^1
10^2
10^3
10^4
10^5
Frequency (hertz)

FIG. 13

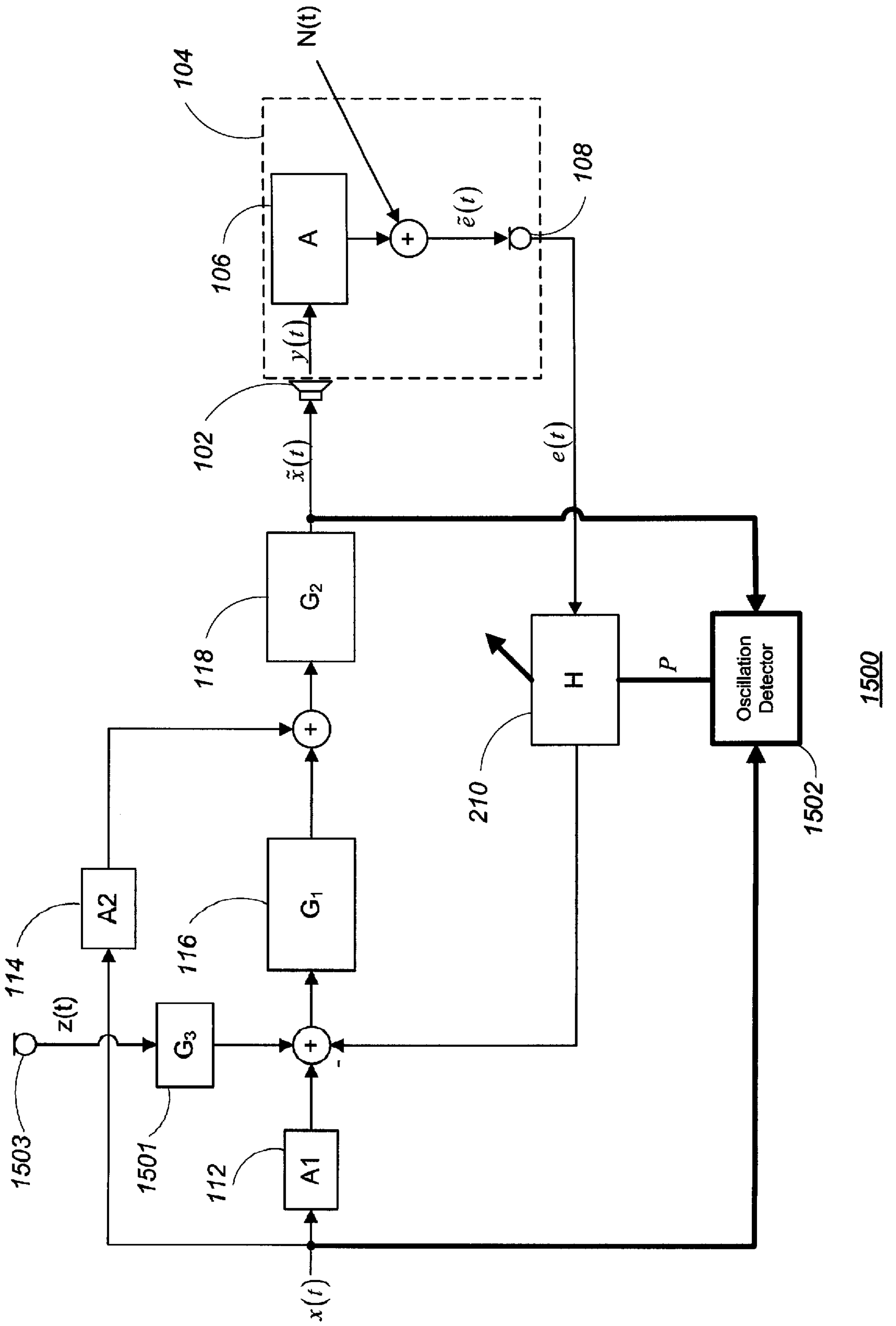

104
N(t)
106
A
+
$\tilde{e}(t)$
108
$y(t)$
102
$\tilde{x}(t)$
$e(t)$
118
G_2
+
H
P
Oscillation Detector
210
1502
1500
114
A2
116
G_1
$z(t)$
G_3
+
-
1503
1501
112
A1
$x(t)$

FIG. 14

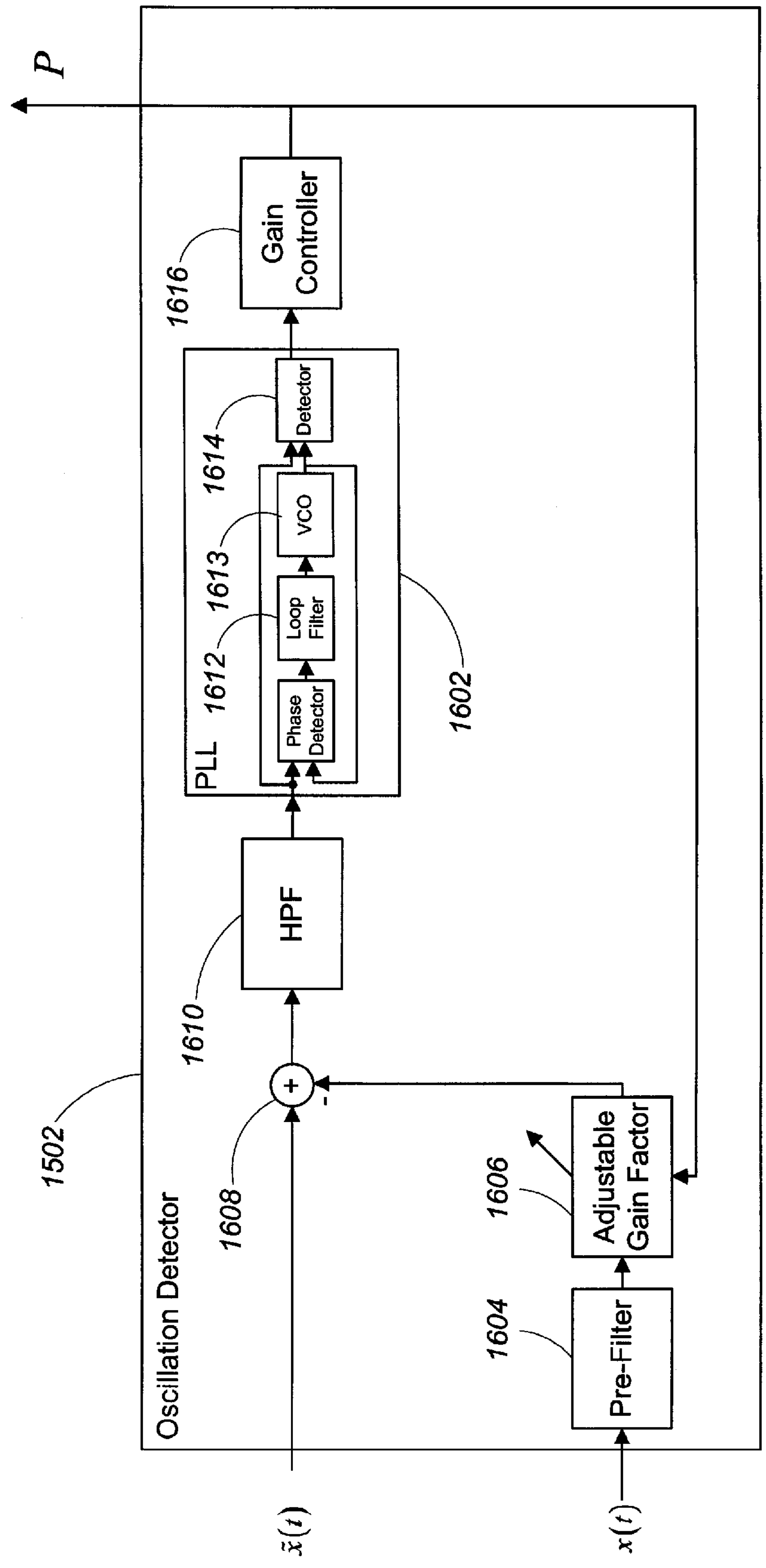
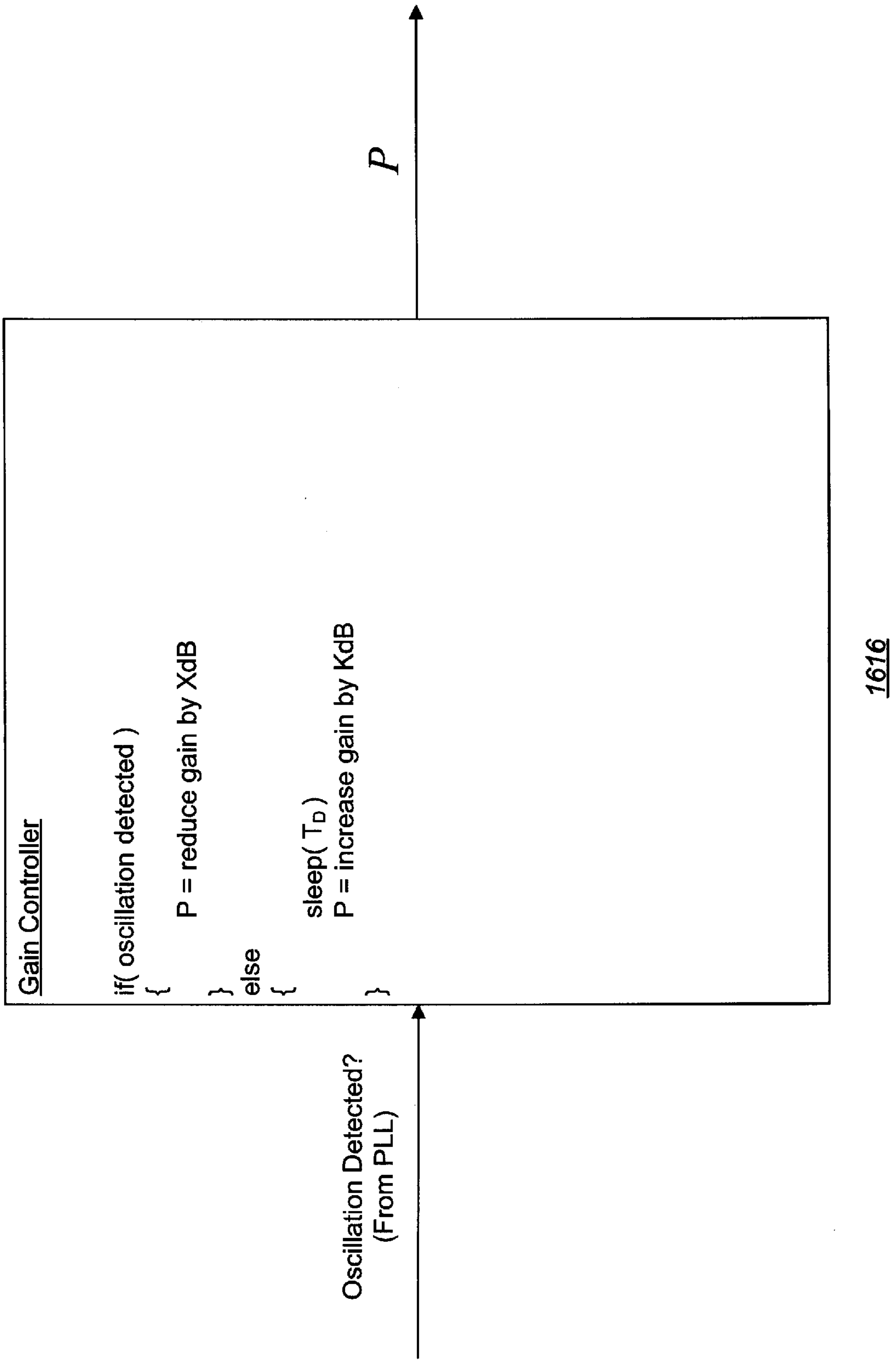
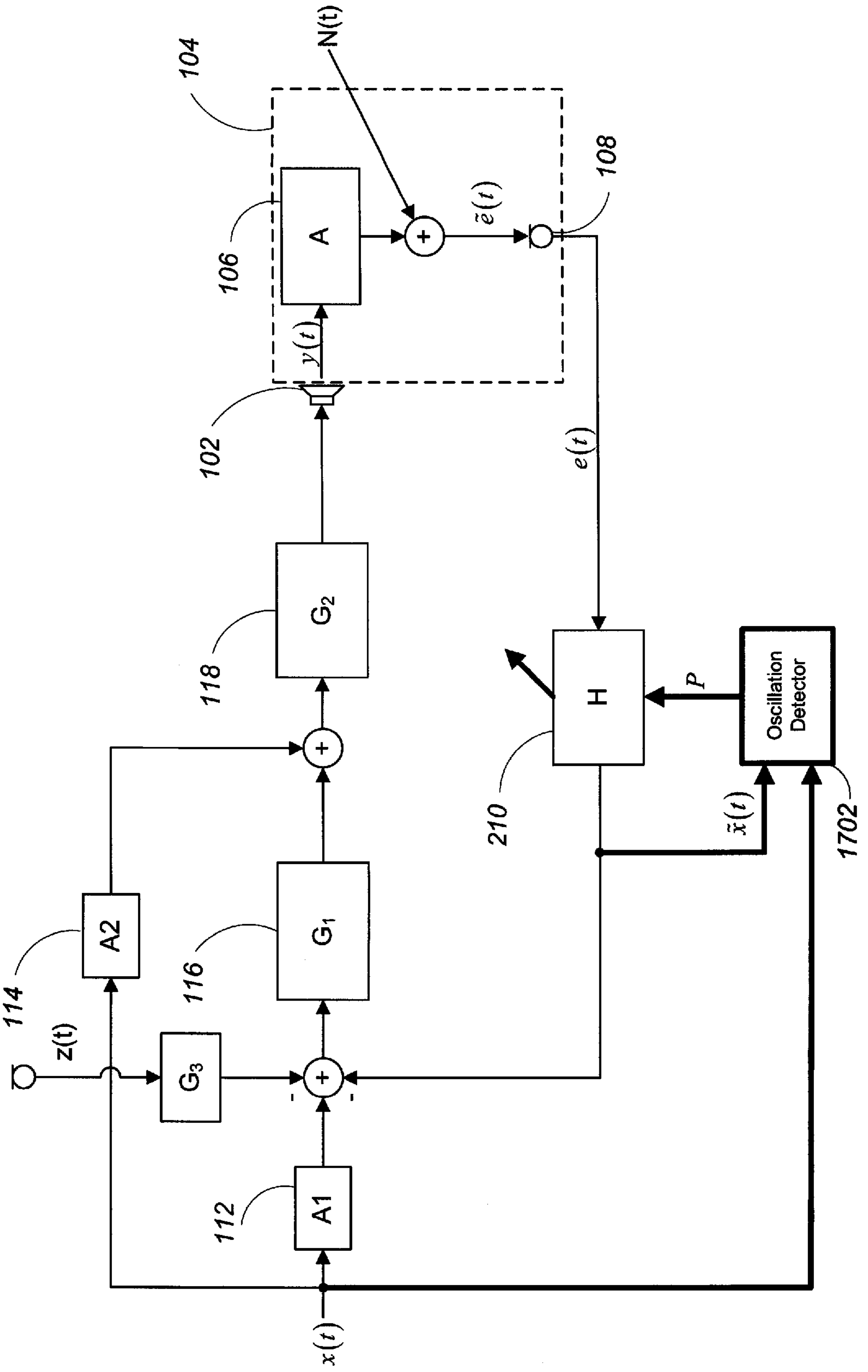

Oscillation Detector
1502
$\tilde{x}(t)$
$x(t)$
1604
Pre-Filter
1606
Adjustable Gain Factor
1608
+
-
1610
HPF
PLL
Phase Detector
1612
Loop Filter
1613
VCO
1614
Detector
1602
1616
Gain Controller
P

FIG. 15



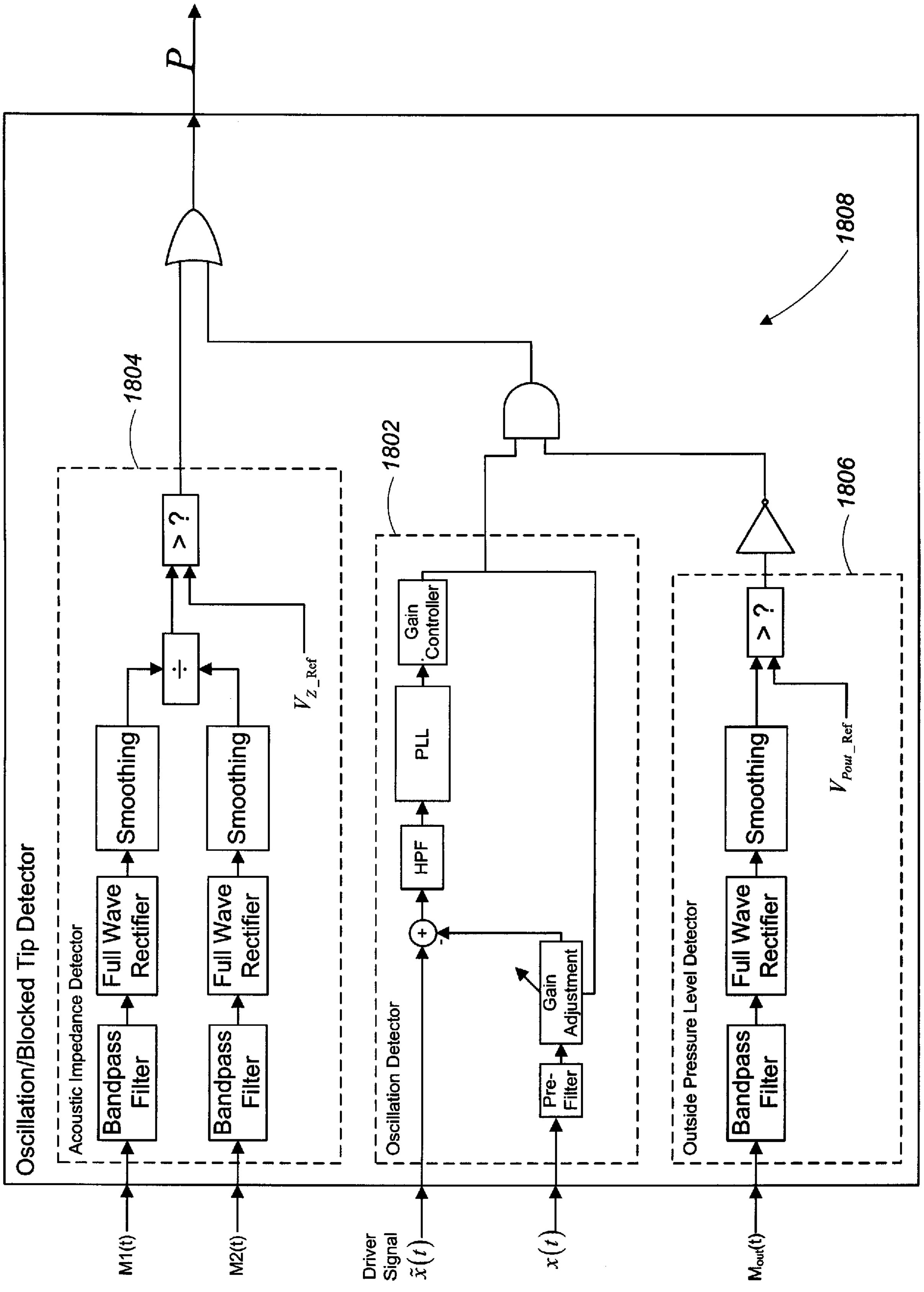
```
if( oscillation detected )
{
        P = reduce gain by XdB
}
else
{
        sleep( $T_D$ )
        P = increase gain by KdB
}
```

FIG. 16


104
N(t)
106
A
+
$\tilde{e}(t)$
108
$y(t)$
102
$e(t)$
118
G_2
+
A2
114
G_1
116
z(t)
G_3
+
-
-
A1
112
$x(t)$
H
210
P
Oscillation Detector
$\tilde{x}(t)$
1702

1700

FIG. 17


P
Oscillation/Blocked Tip Detector
Acoustic Impedance Detector
1804
M1(t)
Bandpass Filter
Full Wave Rectifier
Smoothing
M2(t)
Bandpass Filter
Full Wave Rectifier
Smoothing
÷
> ?
V_{Z_Ref}
Oscillation Detector
1802
Driver Signal $\tilde{x}(t)$
+
-
HPF
PLL
Gain Controller
$x(t)$
Pre-Filter
Gain Adjustment
Outside Pressure Level Detector
1806
$M_{out}(t)$
Bandpass Filter
Full Wave Rectifier
Smoothing
> ?
V_{Pout_Ref}
1808

1810

FIG. 18

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2013/034772

A. CLASSIFICATION OF SUBJECT MATTER
INV. H04R1/10 H04R3/02 G10K11/178
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)
H04R G10K

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

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

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
E	WO 2013/052327 A2 (BOSE CORP [US]; BAKALOS PERICLES [US]; PARTHASARATHI ANAND [US]) 11 April 2013 (2013-04-11) the whole document -----	1-4,6-9, 11-14, 16-19
E	US 2013/129105 A1 (HUA PHONG [FR]) 23 May 2013 (2013-05-23) the whole document -----	1,3,4, 6-9,11, 13,14, 16-19
X	WO 2010/131154 A1 (KONINKL PHILIPS ELECTRONICS NV [NL]; VAN LEEST ADRIAAN J [NL]) 18 November 2010 (2010-11-18)	1-4,7-9, 11-14, 17-19
Y	the whole document ----- -/--	5,6,10, 15,16,20

☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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"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
3 July 2013

Date of mailing of the international search report
10/07/2013

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Streckfuss, Martin

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C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	WO 2010/129272 A1 (BOSE CORP [US]; CARRERAS RICARDO F [US]; BAKALOS PERICLES NICHOLAS [US]) 11 November 2010 (2010-11-11) paragraph [0100] paragraph [0291] - paragraph [0307]; figures 18-21 -----	5,6,10, 15,16,20

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2013/034772

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		WO 2013052327 A2	11-04-2013
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		EP 2597889 A1	29-05-2013
		FR 2983026 A1	24-05-2013
		US 2013129105 A1	23-05-2013
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		EP 2430632 A1	21-03-2012
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		KR 20120026530 A	19-03-2012
		US 2012057720 A1	08-03-2012
		WO 2010131154 A1	18-11-2010
WO 2010129272 A1	11-11-2010	CN 102460567 A	16-05-2012
		EP 2425424 A1	07-03-2012
		EP 2535891 A1	19-12-2012
		JP 2012529061 A	15-11-2012
		WO 2010129272 A1	11-11-2010