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(71) Applicant: **Harman Becker Automotive Systems**
GmbH
76307 Karlsbad (DE)

(72) Inventor: **Christoph, Markus**
94315 Straubing (DE)

(74) Representative: **Westphal, Mussnug & Partner**
Patentanwälte mbB
Werinherstrasse 79
81541 München (DE)

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under INID code 62.

(54) **MICROPHONE ARRAY**

(57) A spherical microphone array may include a sound-diffracting structure that has a closed three-dimensional shape with a surface surrounding the shape and at least two differential microphones mounted flush on the surface of the sound-diffracting structure. At least one of the differential microphones comprises a tube-like

member with two open ends and an omnidirectional microphone is disposed in the tube-like member between its two ends. The omnidirectional microphone is disposed at a position with differing distances to the two ends of the tube-like member.

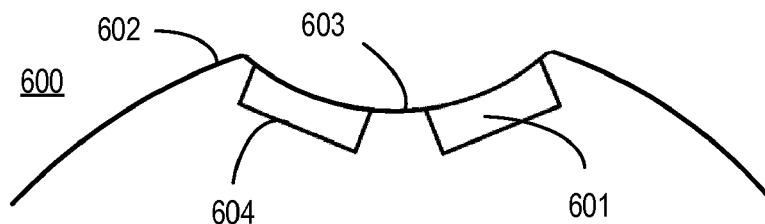


FIG 6

Description

TECHNICAL FIELD

5 **[0001]** The disclosure relates to a microphone array, in particular to a spherical microphone array for use in a modal beamforming system.

BACKGROUND

10 **[0002]** A microphone-array-based modal beamforming system commonly comprises a spherical microphone array of a multiplicity of microphones equally distributed over the surface of a solid or virtual sphere to convert sounds into electrical audio signals and a modal beamformer that combines the audio signals generated by the microphones to form an auditory scene representative of at least a portion of an acoustic sound field. This combination enables the reception of acoustic signals dependent on their direction of propagation. As such, microphone arrays are also sometimes referred to as spatial filters. Spherical microphone arrays exhibit low- and high-frequency limitations so that the sound field can only be accurately described over a limited frequency range. Low-frequency limitations essentially result when the directivity of the particular microphones of the array is poor compared to the wavelength and the high amplification necessary in this frequency range; this leads to high amplification of (self) noise and thus to the need to limit the usable frequency range to a maximum lower frequency. High-frequency issues can be explained by spatial aliasing effects. Similar to temporal aliasing, spatial aliasing occurs when a spatial function (e.g., the spherical harmonics) is under-sampled. For example, at least 16 microphones are needed to distinguish 16 harmonics. In addition, the positions and, depending on the type of sphere used, the directivity of the microphones are important. A spatial aliasing frequency characterizes the upper critical frequency of the frequency range in which the spherical microphone array can be employed without generating any significant artifacts.

25 **[0003]** EP 1 737 268 A1 discloses the use of directional microphones which are not-flush mounted in a rigid structure. In particular, the document discloses a sound field microphone, comprising at least four individual pressure-gradient microphones, called capsules, whose back sides are arranged in space on tangential surfaces of an imaginary sphere with the largest possible symmetry, i.e. on the surfaces of a virtual essentially regular polyhedron. In the interior of the virtual polyhedron, a solid body is arranged, whose volume is greater than 1% of the volume of virtual polyhedron.

30 **[0004]** EP 0 869 697 A2 discloses flush mounting of omnidirectional microphones in a rigid structure. In particular, the document discloses a first-order differential microphone array with a fully steerable and variable responsive pattern that comprises 6 small pressure-sensitive omnidirectional microphones flush-mounted on the surface of a 3/4" diameter rigid nylon sphere. The microphones are advantageously located on the surface at points where included octahedron vertices contact the spherical surface. By selectively combining the three Cartesian orthogonal pairs with scalar weightings, a general first-order differential microphone beam (or a plurality of beams) is realized which can be directed to any angle (or angles) in three-dimensional space.

35 **[0005]** EP 0 664 071 B1 discloses a hearing aid apparatus that employs both an omnidirectional microphone and at least one directional microphone of at least the first order. A switching circuit accepts the signals output from both the omnidirectional microphone and the directional microphone. The switching circuit connects the signal from the omnidirectional microphone to an input of a hearing aid amplifier when the switching circuit is in a first switching state, and connects the output of the equalization circuit to the hearing aid amplifier input when the switching circuit is in a second switching state.

40 **[0006]** EP 2 262 277 A1 discloses an arrangement with multiple pressure gradient transducers in a common housing. In particular, the document discloses a microphone arrangement, comprising at least two pressure gradient transducers, having a first sound inlet opening, which leads to the front, and a second sound inlet opening that leads to the back. The directional characteristic of each transducer comprises an omni portion and a figure-of-eight portion and has a direction of maximum sensitivity, the main direction. A boundary is provided, at which the pressure gradient transducers are arranged, that the main directions of the transducers are inclined relative to each other, and that the acoustic centers of the transducers lie within an sphere whose radius corresponds to the double of the largest dimension of the diaphragms of said transducers.

50 **[0007]** EP 2 773 131 A1 discloses disposing a single omnidirectional microphone at the end of a cavity in a sound diffracting structure. In particular, the document discloses a spherical microphone array with improved frequency range for use in a modal beamformer system that comprises a sound-diffracting structure, e.g. a rigid sphere with cavities in the perimeter of the diffracting structure and a microphone located in or at the ends of said cavities respectively, where the cavities are shaped to form both a spatial low-pass filter, e.g. exhibiting a wide opening, and a concave focusing element so that sound entering the cavities in a direction perpendicular to the perimeter of the diffracting structure converges to the microphones, e.g. by providing a parabolic surface, in order to minimize spatial aliasing.

55 **[0008]** Reducing the unwanted effects of spatial aliasing is widely desired.

SUMMARY

[0009] A spherical microphone array may include a sound-diffracting structure that has a closed three-dimensional shape with a surface surrounding the shape and at least two differential microphones mounted flush on the surface of the sound-diffracting structure. At least one of the differential microphones comprises a tube-like member with two open ends and an omnidirectional microphone is disposed in the tube-like member between its two ends. The omnidirectional microphone is disposed at a position with differing distances to the two ends of the tube-like member.

[0010] Other systems, methods, features and advantages will be or will become apparent to one with skill in the art upon examination of the following detailed description and figures. It is intended that all such additional systems, methods, features and advantages be included within this description, be within the scope of the invention and be protected by the following claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] The system may be better understood with reference to the following description and drawings. The components in the figures are not necessarily to scale, emphasis instead being placed upon illustrating the principles of the invention. Moreover, in the figures, like referenced numerals designate corresponding parts throughout the different views.

Figure 1 is a perspective view of a six-element microphone array mounted in a spherical sound-diffracting structure.

Figure 2 is a perspective view of a microphone array that has a sound-diffracting structure with the polyhedral shape of a 60-sided pentakis dodecahedron.

Figure 3 is a perspective view of a spherical sound-diffracting structure with indentations of the surface formed by conical cavities.

Figure 4 is a cross-sectional view of a rigid sphere with no indentation shapes and an integrated flush-mounted microphone element.

Figure 5 is a cross-sectional view of a rigid sphere with an indentation shaped as an inverse spherical cap in which a differential microphone element is disposed at the bottom.

Figure 6 is a cross-sectional view of a rigid sphere with an indentation shaped as an inverse spherical cap in which two differential microphone elements are disposed, thereby forming a microphone patch.

Figure 7 is a diagram illustrating directivity plots for a first-order differential microphone in accordance with Equation (1), wherein $\alpha = 0.55$.

Figure 8 is a diagram illustrating directivity plots for a first-order differential microphone in accordance with Equation (1), wherein $\alpha = 0.20$.

Figure 9 is a schematic sectional view of a herein not claimed acoustically differentiating differential microphone element.

Figure 10 is a schematic sectional view of an exemplary acoustically differentiating differential microphone element.

Figure 11 is a schematic sectional view of a herein not claimed first exemplary electrically differentiating differential microphone element.

Figure 12 is a schematic sectional view of a herein not claimed second exemplary electrically differentiating differential microphone element.

DETAILED DESCRIPTION

[0012] A schematic illustration of a six-element 3D microphone array 100 mounted in rigid sphere 101, which forms a sound-diffracting structure, is shown in Figure 1. Note that only three of the six microphone elements can be seen in the figure (i.e., microphones 102, 103 and 104), the remaining three microphone elements are hidden on the back side of sphere 100. All six microphone elements are mounted flush on the surface of sphere 100 at points where an inscribed

regular octahedron's vertices would contact the spherical surface. The individual microphone elements are differential microphone elements such as those shown in and described below in connection with Figure 10. In other herein not claimed exemplary microphone arrays, other conventional differential microphone elements may be used.

[0013] Figure 2 shows a perspective view of a 3D microphone array 200 that has the polyhedral shape of a 60-sided pentakis dodecahedron. Although not shown in the figures, microphone array 200 of Figure 2 has a plurality of individual flush-mounted microphone elements, analogous to elements 102, 103 and 104 of Figure 1, distributed around and integrated into different rigid triangular sections 201 of sphere 200, where zero, one or more microphone elements are mounted flush onto the surface of each different triangular section 201. Depending on the particular implementation, the microphone elements may be distributed uniformly or non-uniformly around the polyhedron, with each triangular section 201 having the same number of microphone elements or different triangular sections 201 having different numbers of microphone elements, including some triangular sections 201 that have no microphone elements.

[0014] Figure 3 illustrates a 3D microphone array 300 that has a spherical sound-diffracting structure 301 with microphones 302 embedded in cavities whose dimensions and shapes are optimized to tailor the directivity pattern. Figure 3 shows a circular conical cavity; however, a sectoral cavity or any other appropriately shaped cavity may alternatively be used to form an indentation of the spherical surface. The truncated conical shape of microphone array 300 is designed to increase directivity on both horizontal and vertical planes, whereas a sectoral cavity provides higher directivity on the horizontal plane. The cavity shape can be tailored and optimized to give the best compromise in terms of vertical and horizontal directivity. Directivity is achieved in sound-diffracting structure 301 of Figure 3 due to a combination of obstacle size and cavity design. A person of ordinary skill in the art will appreciate that there are a large variety of shapes of indentations that can be designed.

[0015] The microphone elements in the examples presented in Figures 1-3 are mounted flush on the surface of the sound-diffracting structure (e.g., rigid spheres with or without indentations) as shown in Figures 4-6. Flush-mounted microphone elements are microphone elements that are mounted or integrated into the structure in such a way that there is substantially no protrusion from the surface. Figure 4 shows details of rigid sphere 400, which has no indentations, in which differential microphone element 401 is mounted flush on a surface 402 of rigid sphere 400. Figure 5 shows details of rigid sphere 500, which has an indentation 503, in which differential microphone element 501 is mounted flush on surface 502 of indentation 503 and thus of rigid sphere 500. Figure 6 shows details of rigid sphere 600, which has an indentation 603, in which two differential microphone elements 601 and 604 are mounted flush on a surface 602 of indentation 603 and thus of rigid sphere 600. Omnidirectional microphone elements can also be used instead of two differential microphone elements if their omnidirectional behavior is transformed into differential behavior by a corresponding electronic circuit or by software. The indentations may be shaped, for example, as inverse spherical caps or inverse circular paraboloids.

[0016] In the exemplary microphone arrays shown in Figures 1-3, differential microphone elements (also known as pressure gradient microphones) are employed. For example, a first-order differential microphone element has a general directional pattern E, which can be written as:

$$E(\varphi) = \alpha + (1 - \alpha) \cos(\varphi), \quad (1)$$

wherein φ is the azimuth spherical angle and, typically, $0 \leq \alpha \leq 1$ so that the response is normalized to have a maximum value of 1 at $\varphi = 0^\circ$. Note that the directivity is independent of spherical elevation angle θ due to an assumption of symmetrical rotation. The magnitude of Equation (1) is the parametric expression of the "limaçon of Pascal" algebraic curve, familiar to those skilled in the art. The two terms in Equation (1) can be seen to be the sum of an omnidirectional sensor (i.e., the first term) and a first-order dipole sensor (i.e., the second term), which is the general form of the first-order array. One implicit property of Equation (1) is that for $0 \leq \alpha \leq 1$, there is a maximum at $\theta = 0$ and a minimum at an angle between $\pi/2$ and π . For values of $\alpha > 0.5$, the response has a minimum at π , although there is no zero in the response. A microphone with this type of directivity is typically referred to as a sub-cardioid microphone. An illustrative example of the response for this case is shown in Figure 7, wherein $\alpha = 0.55$. When $\alpha = 0.5$, the parametric algebraic equation has a specific form, which is referred to as a cardioid. The cardioid pattern has a zero response at $\varphi = 180^\circ$. For values of $0 \leq \alpha \leq 0.5$, there is a null at:

$$\varphi_{\text{null}} = \cos^{-1}(\alpha/\alpha - 1). \quad (2)$$

[0017] Figure 8 shows an illustrative directional response corresponding to this case, wherein $\alpha = 0.20$.

[0018] Now referring to Figure 9, a differential microphone element 900 may have a directivity in the approximate shape of a cardioid. Differential microphone element 900 may be a tube-like member (e.g., a substantially u-curved tube

901) with two open ends, also herein referred to as sound inlet ports 902 and 903, and omnidirectional microphone 904 disposed in tube 901 between sound inlet ports 902 and 903 of the tube-like member. Sound inlet ports 902 and 903 are spaced at distance d apart and are defined by juxtaposed end sections of tube 901 that communicate with diaphragm 905 of microphone 904. The two sides 905a and 905b of microphone diaphragm 905 receive sound from the two respective inlet ports 902 and 903. The sound pressure driving the rear of the diaphragm travels through a resistive damping material 906, which is designed to provide a time delay (also referred to as acoustic delay). The dissipative, resistive damping material 906 may be designed to create a proper time delay in order for the net pressure to have the desired directivity.

[0019] Ports 902 and 903, which are separated by distance d , as mentioned above, create net pressure p_{net} on the diaphragm, which may be expressed as:

$$p_{net} = P_{net} \cdot e^{j\omega t} = P \left(1 - e^{j\left(\omega t + \frac{d}{c}\omega \cos(\phi)\right)} \right) e^{j\omega t} \quad (3)$$

wherein $j = \sqrt{-1}$, ω is the frequency of the sound in radians/second, c is the speed of sound, ϕ is the angle of incidence and τ is a time delay introduced by the resistive material. Since time delay τ and distance d between ports 12 and 14 are quite small, the argument of the exponential is small and allows Equation (3) to be approximated by:

$$p_{net} \approx Pj \left(\omega t + \frac{d}{c}\omega \cos(\phi) \right) e^{j\omega t}. \quad (4)$$

[0020] Material 906 may be designed to create the proper time delay in order for the net pressure to have the desired directivity. If material 906 is represented by an equivalent low-pass electronic circuit, the transfer function of material 906 is:

$$H = \frac{1}{1+j\omega RC}, \quad (5)$$

wherein R is the equivalent resistance and C is the equivalent capacitance. The phase delay ψ due to this circuit is:

$$\psi = -\arctan(\omega RC) \quad (6)$$

and time delay τ is given by:

$$\tau = \frac{d\phi}{d\omega} = \frac{1}{1+(\omega RC)^2} \frac{1}{RC}. \quad (7)$$

[0021] Operating the filter in the passband ($\omega < 1/(RC)$) leads to a time delay of

$$\tau = \frac{1}{RC}. \quad (8)$$

If the resistive material is selected to create a time delay given by $\tau = d/c$, the net pressure becomes:

$$P_{net} = j\omega \frac{d}{c} (1 + \cos(\phi)). \quad (9)$$

The term $1+\cos(\phi)$ gives the familiar cardioid directivity pattern.

[0022] It is important to note that the net pressure on the directional microphone is proportional to ω and thus has a

6 dB per octave slope. The net pressure is also diminished in proportion to distance d between the ports. Reducing the overall size of the sensor thus results in a proportional loss of sensitivity.

[0023] Note that the 6 dB per octave slope and the dependence on dimension d remain even in microphones without the resistive material ($\tau = 0$) in Equation (4). A microphone without the resistive material but with different distance

between the omnidirectional microphone and the sound inlet ports is shown in Figure 10.

[0024] Differential microphone element 1000 may comprise a substantially u-curved tube 1001, with two sound inlet ports 1002 and 1003, and an omnidirectional microphone 1004 disposed in tube 1001 between sound inlet ports 1002 and 1003 of the tube-like member. Sound inlet ports 1002 and 1003 are spaced at a distance d apart, and are defined by juxtaposed end sections of tube 1001 that communicate with diaphragm 1005 of microphone 1004. The two sides 1005a and 1005b of microphone diaphragm 1005 receive sound from the two respective inlet ports 1002 and 1003. The sound pressure driving rear side 1005b of the diaphragm travels a longer way compared to front side 1005a and thus provides a time delay relative to front side 1005a.

[0025] It is noted for the sake of completeness that differential microphone characteristics may be achieved not only with a purely acoustic differential microphone assembly, but also electro-acoustically. Referring to Figure 11, an electro-acoustic first-order differential microphone element 1100 may include acoustics part 1101 and electronics part 1102. Acoustics part 1101 features two omnidirectional microphones 1103 and 1104 arranged at distance d from each other. Within electronics part 1102, the outputs of omnidirectional microphones 1003 and 1104 are subtracted from each other by differencing amplifier 1105. Before this subtraction, the output of omnidirectional microphone 1104 is passed through delay element 1106 to delay the outputs of the two omnidirectional microphones 1103 and 1104 relative to each other. This element may be, for example, an all-pass filter or time delay circuit. The output of differencing amplifier 1105 is passed through equalizing filter 1107 to compensate for frequency-dependent gain values of the circuit.

[0026] Figure 12 shows a schematic diagram of another first-order full-band differential microphone element 1200 based on an adaptive back-to-back cardioid system. In differential microphone element 1200, signals from two microphones 1201 and 1202 are delayed by delay time T at delay elements 1203 and 1204, respectively. The delayed signal from microphone 1201 is subtracted from the undelayed signal from microphone 1202 at subtraction element 1205 to form a forward-facing cardioid signal. Similarly, the delayed signal from microphone 1202 is subtracted from the undelayed signal from microphone 1201 at subtraction element 1206 to form a backward-facing cardioid signal.

[0027] While various embodiments of the invention have been described, it will be apparent to those of ordinary skill in the art that many more embodiments and implementations are possible within the scope of the invention. Accordingly, the invention is not to be restricted except in light of the attached claims and their equivalents.

Claims

1. A spherical microphone array comprising:

a sound-diffracting structure (100, 200, 300, 400, 500, 600) that has a closed three-dimensional shape with a surface (101, 402, 502, 602) surrounding the shape; and
at least two differential microphones (102-104, 302, 401, 501, 601, 604, 1000) mounted flush on the surface of the sound-diffracting structure, wherein
at least one (1000) of the differential microphones (102-104, 302, 401, 501, 601, 604, 1000) comprises a tube-like member (1001) with two open ends (1002, 1003) and an omnidirectional microphone (1005) disposed in the tube-like member (1001) between its two ends (1002, 1003); and
the omnidirectional microphone (1005) is disposed at a position with differing distances to the two ends (1002, 1003) of the tube-like member (1001).

2. The microphone array of claim 1, wherein the sound-diffracting structure (100, 200, 300, 400, 500, 600) has the shape of a sphere or polyhedron.

3. The microphone array of claim 1 or 2, wherein an acoustic delay element is disposed between one end (1003) of the tube-like member (1001) and the omnidirectional microphone (1005).

4. The microphone array of any of the preceding claims, wherein the tube-like member (1001) is u-curved.

5. The microphone array of any of the preceding claims, further comprising at least one indentation (503, 603) in the perimeter of the diffracting structure (500, 600), wherein at least one differential microphone (501, 601, 604, 1000) is disposed in the at least one indentation (503, 603).

EP 3 506 650 A1

6. The microphone array of any of the preceding claims, wherein the surface of the diffracting structure (101) has at least one indentation formed thereon and at least one differential microphone is disposed in the at least one indentation.
- 5 7. The microphone array of claim 5 or 6, wherein the at least one indentation (503, 603) is shaped as an inverse spherical cap or inverse circular paraboloid.
8. The microphone array of any of the preceding claims, wherein the walls of the indentation (503, 603) are sound-reflective.

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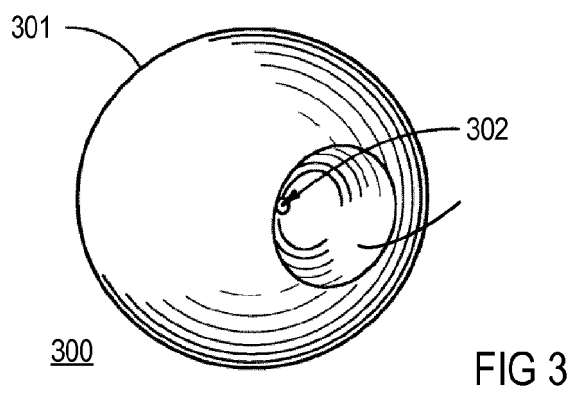
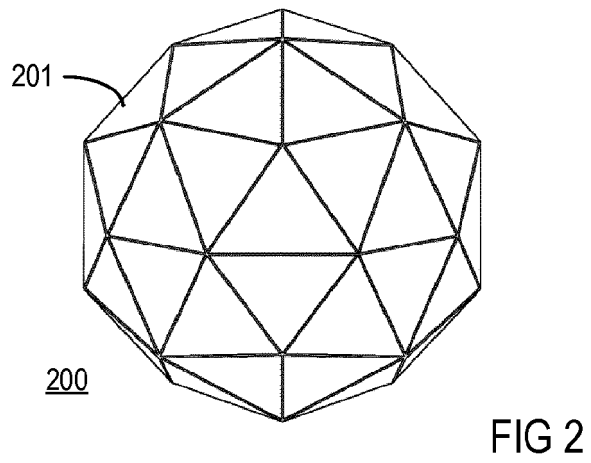
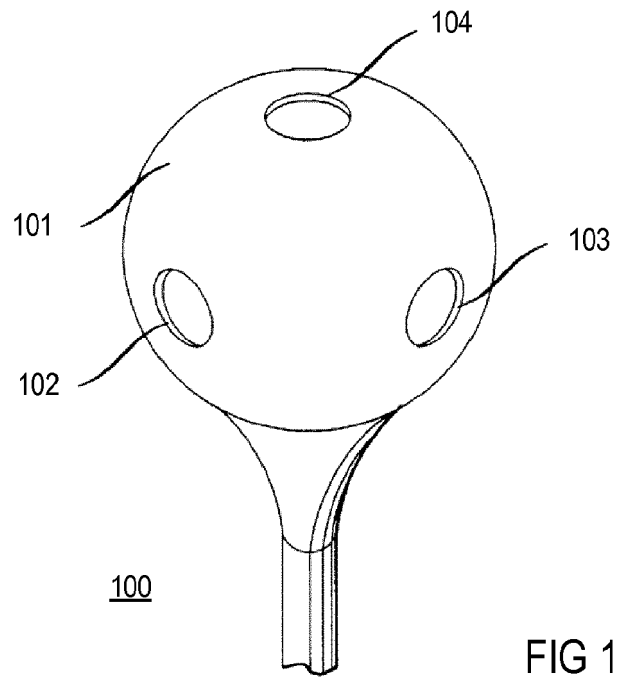
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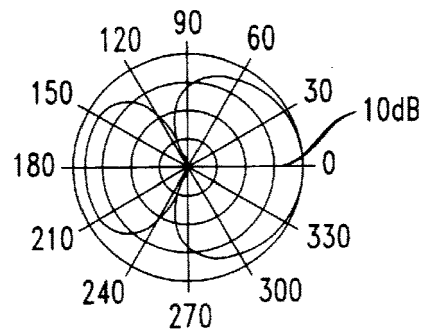
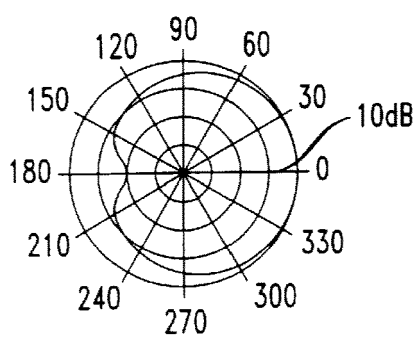
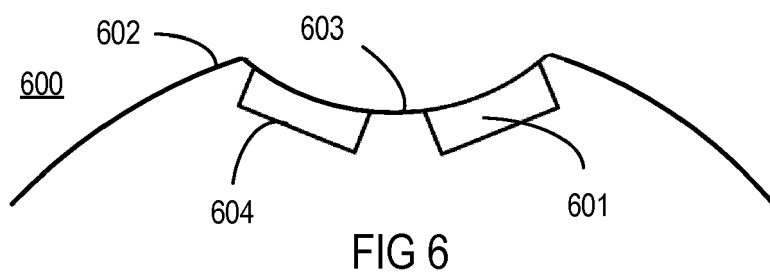
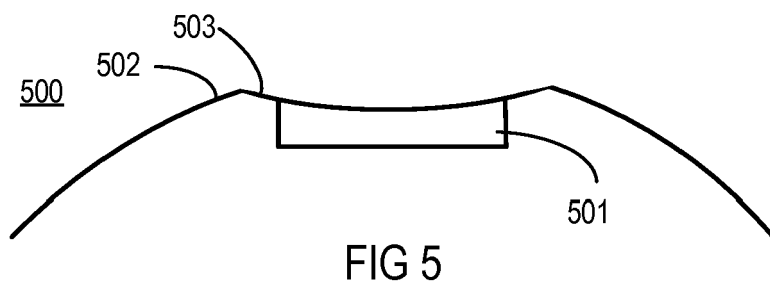
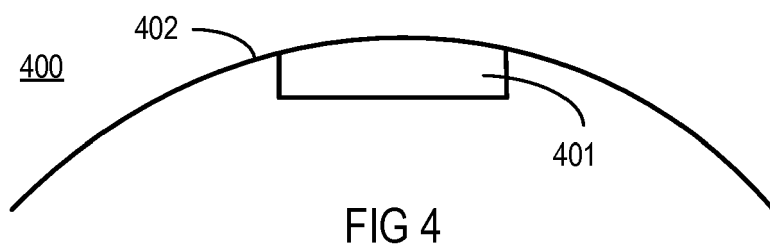
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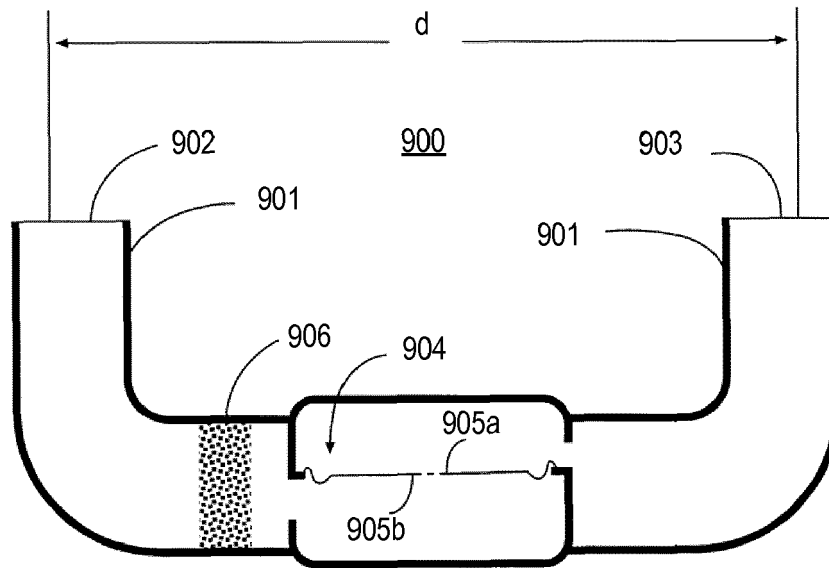


FIG 9

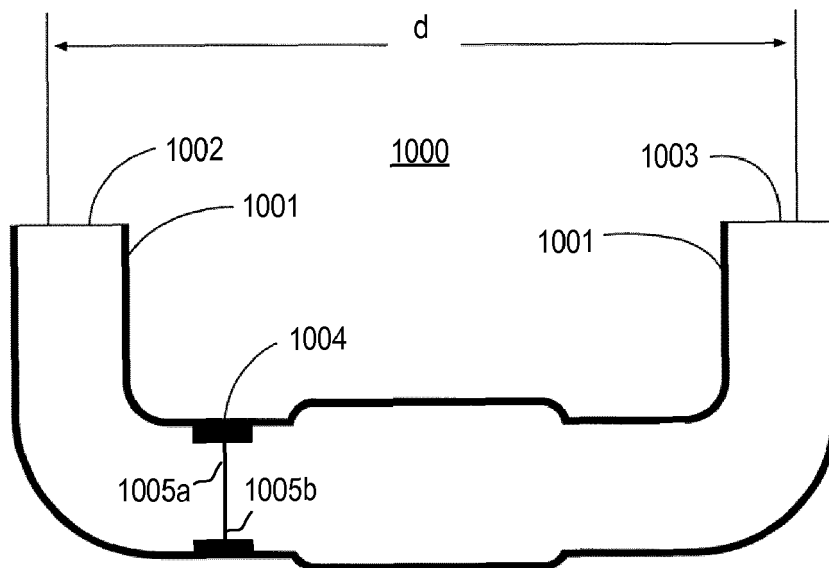


FIG 10

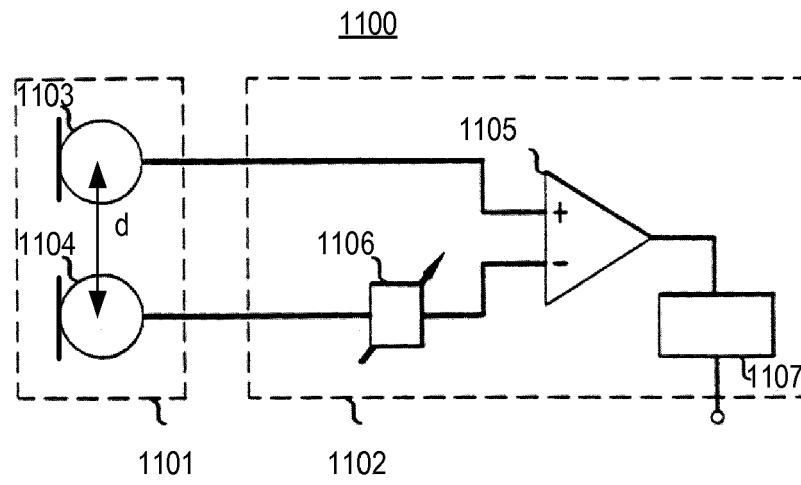


FIG 11

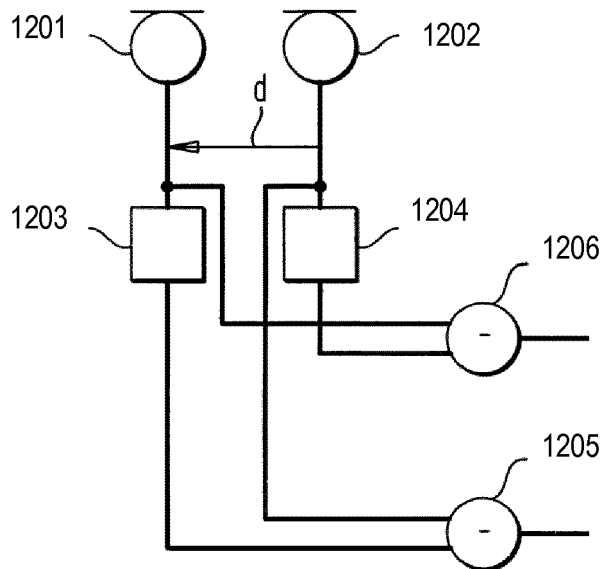


FIG 12



EUROPEAN SEARCH REPORT

 Application Number
 EP 19 15 7791

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The present search report has been drawn up for all claims			
Place of search The Hague		Date of completion of the search 28 March 2019	Examiner Fachado Romano, A
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