(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) EP 2 773 131 A1

(12) EUROPEAN PATENT APPLICATION

(43) Date of publication:
03.09.2014 Bulletin 2014/36

(51) Int Cl.:
H04R 1/40 *(2006.01)*

(21) Application number: **13156983.2**

(22) Date of filing: **27.02.2013**

(84) Designated Contracting States:
AL AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HR HU IE IS IT LI LT LU LV MC MK MT NL NO PL PT RO RS SE SI SK SM TR
Designated Extension States:
BA ME

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(54) Spherical microphone array

(57) A spherical microphone array with improved frequency range for use in a modal beamformer system is disclosed 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 respecitively, 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.

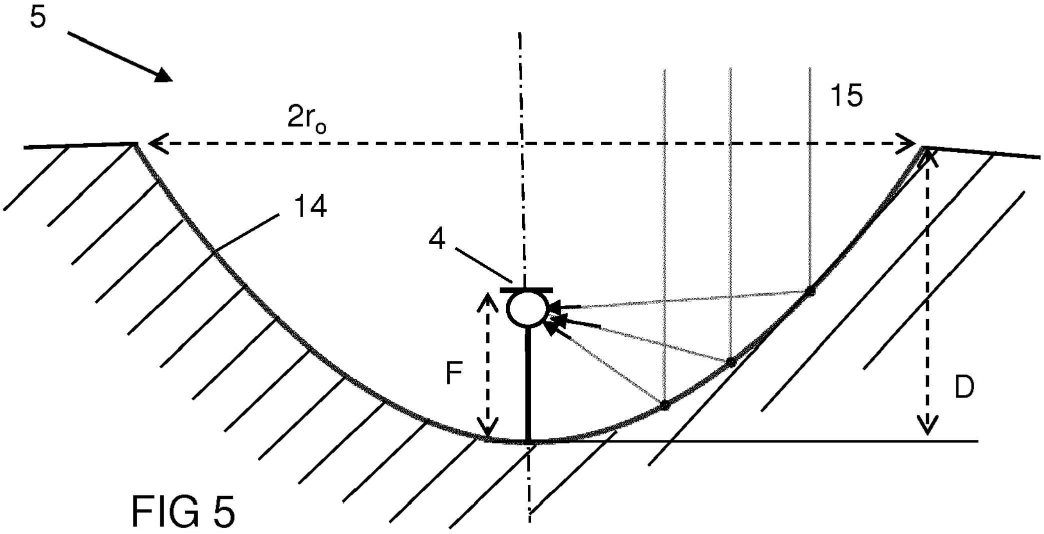

FIG 5

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Description

BACKGROUND

[0001] 1. Technical Field

[0002] The embodiments described herein relate to a spherical microphone array, in particular to a spherical microphone array for use in a modal beamforming system.

2. Related Art

[0003] A microphone array-based modal beamforming system commonly comprises a spherical microphone array of four or more microphones equally distributed over the surface of a solid or virtual sphere for converting sounds into electrical audio signals and a modal beamformer combining 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 picking up 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 soundfield 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 wave-length and the high amplification, necessary in this frequency range, which leads to a high amplification of (self) noise and thus to the need to limit the usable frequency range up to a maximum lower frequency. High-frequency issues can be explained by spatial aliasing effects. Similar to time aliasing, spatial aliasing occurs when a spatial function, e.g., the spherical harmonics, is undersampled. For example, in order to distinguish 16 harmonics, at least 16 microphones are needed. 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. Reducing the unwanted effects of spatial aliasing is widely desired.

SUMMARY

[0004] A spherical microphone array for use in a modal beamformer system is disclosed that comprises a sound-diffracting structure having a closed three-dimensional shape; at least four cavities in the perimeter of the diffracting structure; and a microphone disposed in or at the ends of respective ones of the cavities, where the at least four cavities are shaped to form both a spatial low-pass filter and a focusing element so that sound entering the cavities in a direction perpendicular to the perimeter of the diffracting structure at the position of the microphone(s) is collected and transferred to the microphone(s) with the least attenuation, whereas signals entering from other directions are attenuated by diffraction.

[0005] Other systems, methods, features and advantages of the invention will be, or will become, apparent to those skilled in the art upon examination of the following figures and the detailed description. 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

[0006] The invention can be better understood with reference to the following drawings and description. 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 reference numerals designate corresponding parts throughout the different views.

FIG. 1 is a schematic diagram of an exemplary microphone array for use in a modal beamformer system;

FIG. 2 is a three-dimensional view of an alternative diffracting structure corresponding to the sphere shown in FIG. 1 having the shape of a truncated icosahedron;

FIG. 3 is a cross-sectional view of the cavity of FIG. 1 shaped as an inverse spherical cap 10 with a sound-reflective surface;

FIG. 4 is a three-dimensional view of the spherical cap of FIG. 3 as a portion of a sphere cut off by a plane;

FIG. 5 is a cross-sectional view of the cavity of FIG. 1 shaped as an inverse paraboloid;

FIG. 6 is a cross-sectional view of the cavity of FIG. 1 having an alternative inverse paraboloidal shape; and

FIG. 7 is a three-dimensional view of the cavity shown in FIG. 6.

DETAILED DESCRIPTION

[0007] FIG. 1 is a schematic diagram of an exemplary array 1 of microphones 4 (herein referred to as microphone array 1) for use in a modal beamformer system 2 that further includes a beamformer unit 3 connected downstream of the microphone array 1. Microphones 4 may be disposed in a regular fashion over the surface of the rigid sphere. Modal beamformer 3 may include a decomposer (also known as eigenbeam former), steering unit, compensation unit, and summation unit. Each microphone 4 of microphone array 1 generates an audio signal that is transmitted to modal beamformer unit 3 via some suitable (e.g., wired or wireless) connection.

[0008] For example, microphone array 1 may comprise 32 microphones 4 mounted in cavities 5 arranged at the surface of an acoustic rigid sphere 6 in a "truncated icosahedron" pattern serving as a diffracting structure. There exist only five possibilities to divide the surface of a sphere into equal areas. These five geometries, which are known as regular polyhedrons or Platonic solids, consist of four,six, 12, and 20 faces, respectively. Another geometry that comes close to a regular division is the truncated icosahedron, which is an icosahedron with vertices cut off (thus, the term "truncated"). This results in a solid consisting of 20 hexagons and 12 pentagons. Other possible microphone arrangements include the center of the of an icosahedron faces (20 microphones) or the center of the edges of an icosahedron (30 microphones).

[0009] An alternative diffracting structure corresponding to the sphere shown in FIG. 1 and having the shape of truncated icosahedron 7 is schematically shown in FIG. 2. In particular, truncated icosahedron 7 is configured to carry 32 microphones and includes icosahedron 8 (Platonic solid with 20 faces) and dodecahedron 9 (Platonic solid with 12 faces). Such an arrangement, where the 12 pentagon's of dodecahedron 8 are placed at the poles of a sphere (six at each pole) and the residual 20 hexagons are placed around the equator, leading there to a somewhat higher sensor-density there, provides higher accuracy in acoustical applications since humans also have a higher localization accuracy in the horizontal plane than in the vertical plane.

[0010] In general, the more microphones used, i.e., the lower the inter-microphone distance, the higher the upper maximum frequency will be. On the other hand, the cost increases with the number of microphones. The upper maximum frequency, also known as spatial aliasing frequency f_{Alias} as set forth in Equation (1), characterizes the upper critical frequency of the frequency range in which the spherical microphone array can be employed without generating any significant artifacts.

$$f_{Alias} = c/(2 \cdot d_{Mic}) = c/(2 \cdot a \cdot \gamma_{Mic}), \tag{1}$$

in which c is the speed of sound, d_{Mic} is the angular distance between two microphones of the array, a is the radius of the sphere of the microphone array and γ_{Mic} is the differential angle of two microphones.

[0011] In the arrangement shown in FIG. 1, each microphone 4 positioned at the center of a pentagon has five neighbors at a distance of 0.65a, where a is again the radius of sphere 6. Each microphone 4 positioned at the center of a hexagon has six neighbors, of which three are at a distance d_{Mic} of 0.65a and the other three are at a distance of 0.73a. Applying the sampling theorem ($d_{Mic} < \lambda/2$, λ being the wavelength) and taking the worst case, the maximum frequency is given by Equation (2) as follows:

$$f_{Alias} = c/(2 \cdot 0.73a). \tag{2}$$

[0012] For a common sphere in which the microphones are arranged on its surface and not in cavities, this results, for example, in an upper frequency limit of 4.7 kHz when radius a = 5cm. In practice, a slightly higher maximum frequency can be expected since most microphone distances are less than 0.73a, namely 0.65a. The upper frequency limit can be increased by reducing the radius of the sphere. On the other hand, reducing the radius of the sphere would reduce the achievable directivity at low frequencies.

[0013] One way of improving spherical microphone arrays is to make the microphones more directive. The theory behind this is that the directivity of each sensor should be as close as possible to the desired mode (eigenbeam), which corresponds to high-degree harmonics having a null contribution. A more directive sensing can be obtained, locating omnidirectional microphones at the end of cavities within the sphere as disclosed in US patent application publication

2007/0110257A and in Nicolas Epain and Jerome Daniel's paper, "Improving Spherical Microphone Arrays", presented at the 124th Convention of the Audio Engineering Society, 2008 May 17-20, Amsterdam, The Netherlands.

[0014] Another approach to preventing the microphone from receiving the high-degree spherical harmonics is to use spatial low-pass filtering, i.e., to make the microphones less sensible to fast variations of the sound field over the surface of the sphere. This is possible if each microphone of the array is able to measure the sound field on an extended area around its angular position. This can be achieved by using larger-membrane microphones. These microphones integrate the pressure variations over their membranes, which can be seen as spatial low-pass filtering.

[0015] In the microphone array described herein, cavities 5 are shaped to form both a spatial low-pass filter and a focusing element so that sound entering the cavities from a direction perpendicular to the perimeter of the sphere is collected and transferred to the microphone(s) with the least attenuation. Low-pass filtering may be provided, for example, by cavity shapes whose opening areas are larger than the membrane areas of the microphones. Focusing may be achieved by cavity shapes that concentrate acoustic waves coming in to the cavity along an axis perpendicular to the perimeter of the sphere, at a particular point where the respective microphone is to be arranged. Waves coming in from directions other than perpendicular are reflected (diffracted) by the walls of the cavity, so they do not make their way to the microphone disposed in the cavity.

[0016] FIG. 3 shows cavity 5 shaped as an inverse spherical cap 10 with a sound reflective surface. As depicted in FIG. 4, a spherical cap 11 is a portion of a sphere 12 cut off by a plane 12. If plane 13 passes through the center of sphere 12 so that the height of the cap is equal to the radius of the sphere, the spherical cap is called a dome or hemisphere. Accordingly, the inverse cap 10 is the cavity into which cap 11 fits. At the bottom of the inverse cap 10, i.e., at the end of cavity 5, microphone 4 is disposed, which may be an omnidirectional microphone with a large membrane. The diameter $2r_o$ (area) of the cavity's front opening is e.g., more than two times larger than the diameter $2r_m$ (area) of microphone 4's membrane.

[0017] FIG. 5 shows cavity 5 shaped as an inverse paraboloid 14, also known as a circular parabola, with a sound-reflective surface. Its shape is part of a circular paraboloid, that is, the surface generated by a parabola revolving around its axis. The reflective inverse paraboloid 14 transforms an incoming plane wave traveling along the axis of the inverse paraboloid 14 into a spherical wave converging toward a focal point where microphone 4 is disposed.

[0018] The dimensions of a symmetrical paraboloid are related by Equation (3):

$$4FD = r_o^2, \tag{3}$$

where F is the focal length, D is the depth of the paraboloid (measured along the axis of symmetry from the vertex to the plane of the rim), and r_o is the radius of the rim (half of the diameter $2r_o$ of the rim).

[0019] FIG. 6 is a cross-sectional view of cavity 5 having an alternative inverse paraboloidal shape 16 whose depth D is larger than the diameter $2r_o$ of the rim ($D > 2r_o$), in contrast to the previous examples where $D < 2r_o$. A three-dimensional view of cavity 16 of FIG. 6 is shown in FIG. 7.

[0020] While exemplary embodiments are described above, it is not intended that these embodiments describe all possible forms of the invention. The words used in the specification are words of description rather than limitation, and it is understood that various changes may be made without departing from the spirit and scope of the invention. Additionally, the features of various implementing embodiments may be combined to form further embodiments of the invention.

Claims

1. A spherical microphone array comprising:

    a sound-diffracting structure having a closed three-dimensional shape;
    at least four cavities in the perimeter of the diffracting structure; and
    a microphone disposed in or at the ends of respective ones of the cavities, where
    the at least four cavities are shaped to form both a spatial low-pass filter and a focusing element so that sound entering the cavities in a direction perpendicular to the perimeter of the diffracting structure at the position of the microphone(s) is collected and transferred to the microphone(s) with the least attenuation, whereas signals entering from other directions are attenuated by diffraction.

2. The sensor array of claim 1, wherein the cavities are shaped as inverse spherical caps.

3. The sensor array of claim 2, wherein the microphones are disposed at the end of the cavities shaped as inverse spherical caps.

4. The sensor array of claim 1, wherein the cavities are shaped as inverse circular paraboloids.

5. The sensor array of claim 4, wherein the microphones are disposed at the focal points of the cavities shaped as paraboloids.

6. The sensor array of any of claims 1 through 5, wherein the diffracting structure is a rigid sphere.

7. The sensor array of any of claims 1 through 5, wherein the diffracting structure includes the form of a Platonic solid or a combination of at least two Platonic solids.

8. The sensor array of claim 7, wherein the diffracting structure includes the form of an icosahedron, a dodecahedron or a combination thereof.

9. The sensor array of any of claims 1 through 8, wherein the microphones are omni-directional microphones.

10. The sensor array of any of claims 1 through 9, wherein the walls of the cavities are configured to reflect sound.

11. The sensor array of any of claims 1 through 10, wherein the microphones have a membrane with a first diameter and the cavities have an opening with a rim of a second diameter, the first diameter being smaller than the second diameter.

12. The sensor array of claim 11, wherein the first diameter is smaller than half of the second diameter.

13. The sensor array of any of claims 1 through 12, wherein each microphone is disposed in a regular fashion over the surface of the sphere.

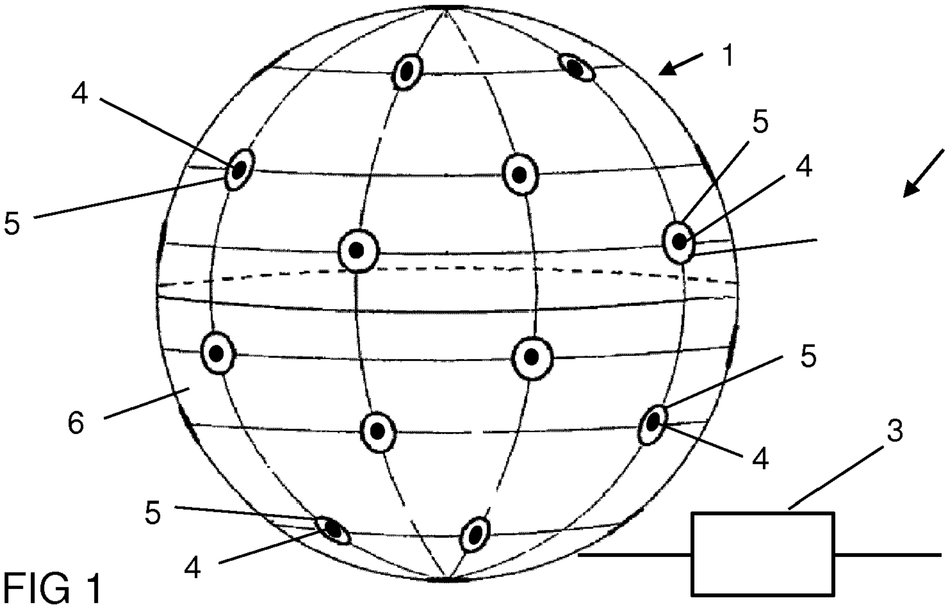

FIG 1

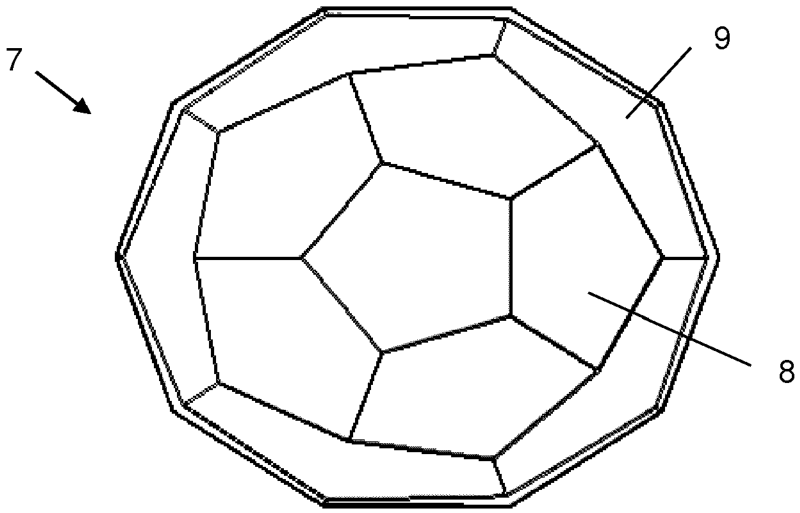

FIG 2

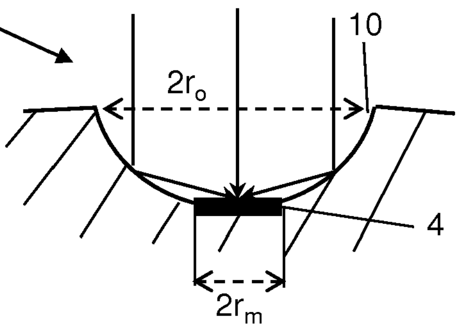

FIG 3

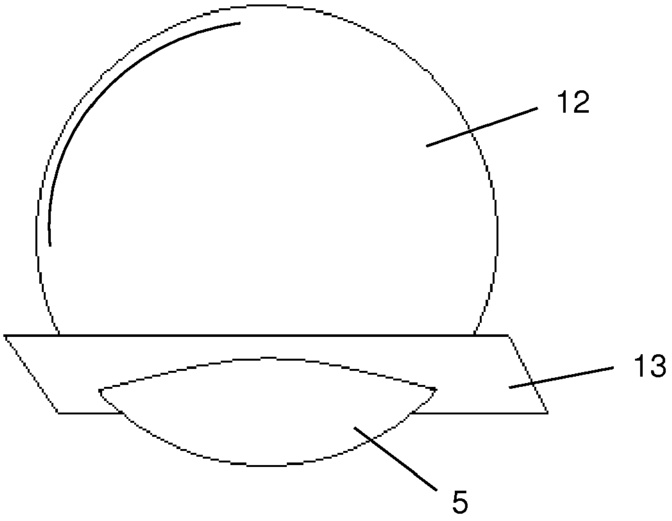

FIG 4

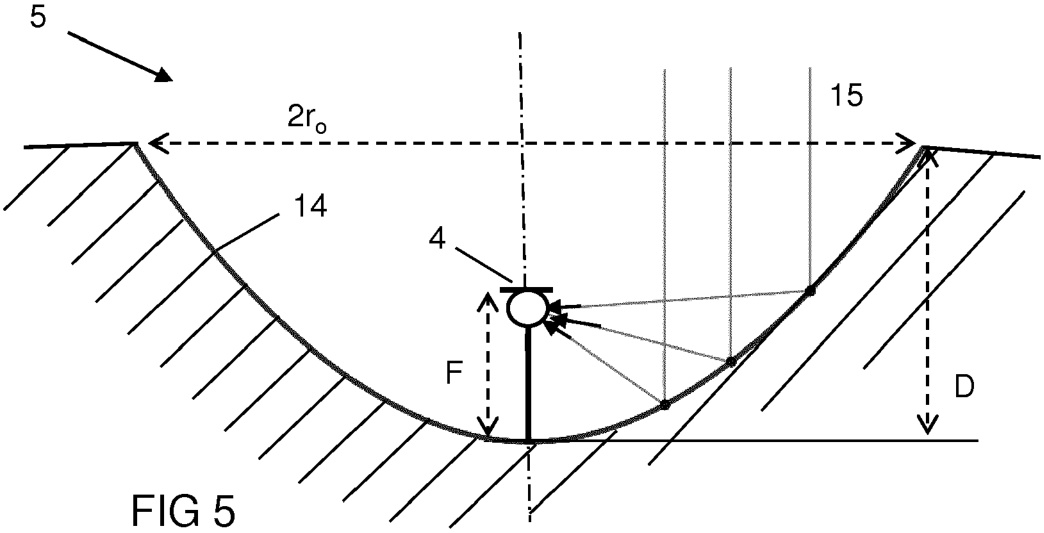

FIG 5

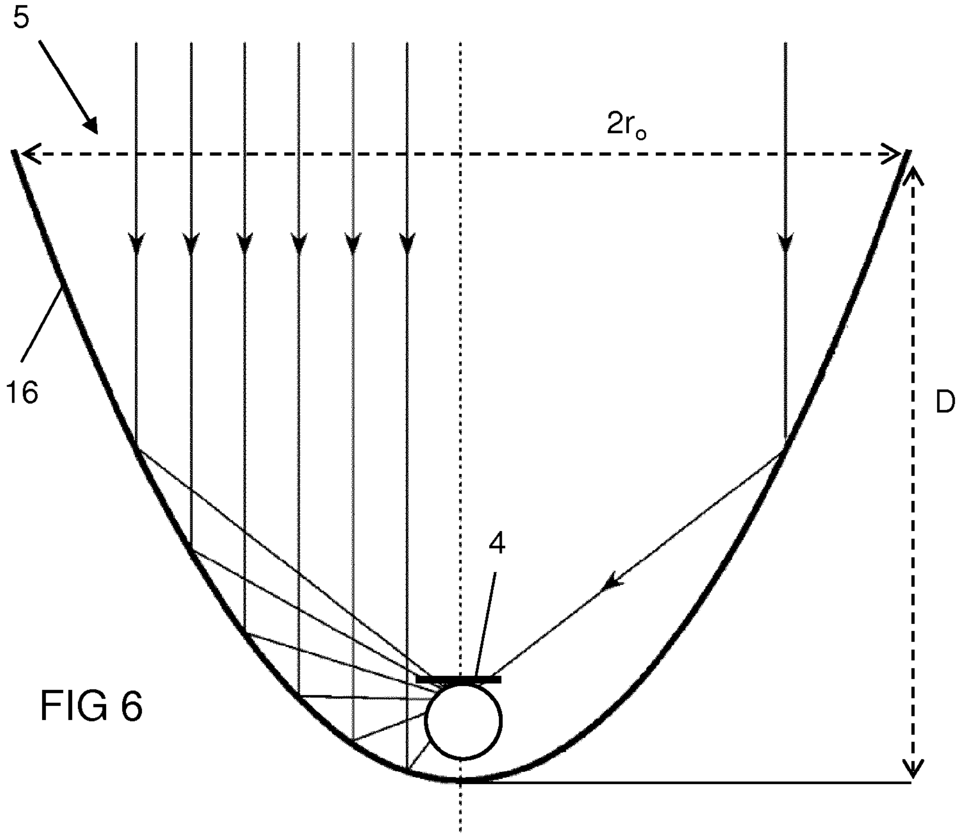

FIG 6

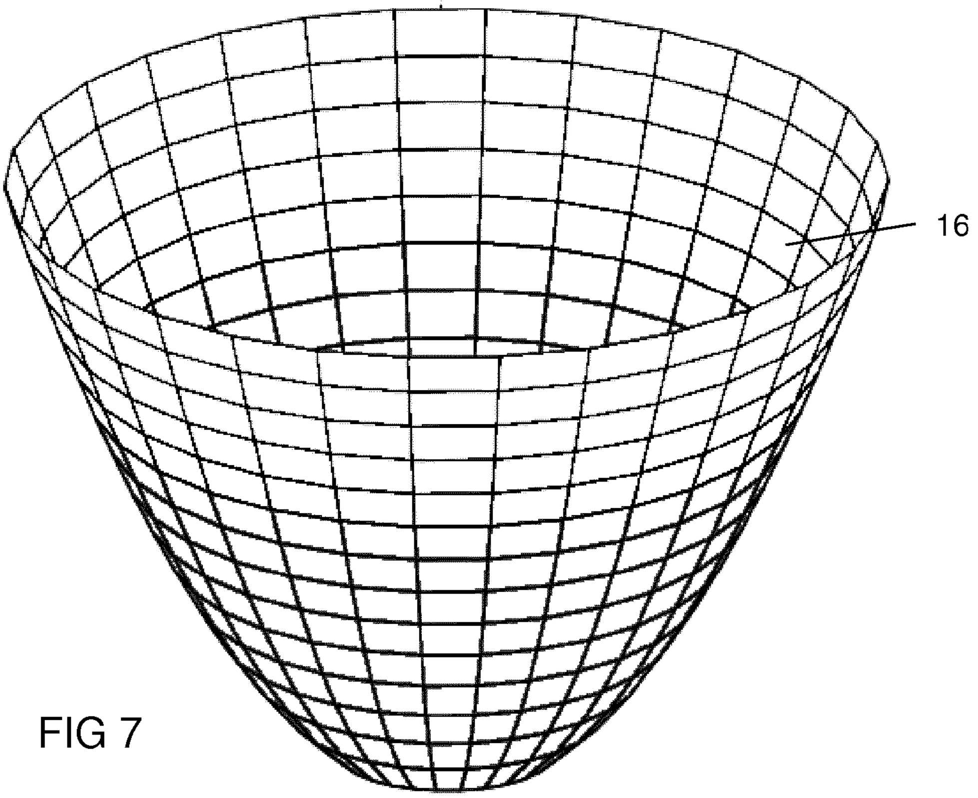

FIG 7

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EUROPEAN SEARCH REPORT

Application Number
EP 13 15 6983

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The present search report has been drawn up for all claims

1

Place of search	Date of completion of the search	Examiner
The Hague	20 December 2013	Will, Robert

EPO FORM 1503 03.82 (P04C01)

CATEGORY OF CITED DOCUMENTS

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EUROPEAN SEARCH REPORT

Application Number
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DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
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			TECHNICAL FIELDS SEARCHED (IPC)

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For more details about this annex : see Official Journal of the European Patent Office, No. 12/82

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