

## IMPROVED NON-ROUND FLUID FILLED LENS OPTIC

## BACKGROUND

Field

[0001] Embodiments of the present invention relate to fluid-filled lenses and in particular to variable fluid-filled lenses.

Background Art

[0002] Basic fluid lenses have been known since about 1958, as described in U.S. Pat. No. 2,836,101, incorporated herein by reference in its entirety. More recent examples may be found in “Dynamically Reconfigurable Fluid Core Fluid Cladding Lens in a Microfluidic Channel” by Tang et al., Lab Chip, 2008, vol. 8, p. 395, and in WIPO publication WO2008/063442, each of which is incorporated herein by reference in its entirety. These applications of fluid lenses are directed towards photonics, digital phone and camera technology and microelectronics.

[0003] Fluid lenses have also been proposed for ophthalmic applications (see, e.g., U.S. Patent No. 7,085,065, which is incorporated herein by reference in its entirety). In all cases, the advantages of fluid lenses including a wide dynamic range, ability to provide adaptive correction, robustness and low cost have to be balanced against limitations in aperture size, tendency to leak and consistency in performance. The '065 patent, for example, has disclosed several improvements and embodiments directed towards effective containment of the fluid in the fluid lens to be used in ophthalmic applications, although not limited to them (see, e.g., U.S. Patent No. 6,618,208, which is incorporated by reference in its entirety). Power adjustment in fluid lenses has been effected by injecting additional fluid into a lens cavity, by electrowetting, application of ultrasonic

impulse, and by utilizing swelling forces in a cross-linked polymer upon introduction of a swelling agent such as water.

[0004] In all cases, there are several key limitations in fluid lens technology that need to be overcome to optimize the commercial appeal of this technology. For example, the thickness of fluid lenses is generally greater than conventional lenses of the same power and diameter. Additionally, it is not currently possible to provide a variation of spherical power as well as astigmatism across the lens optic using fluid lens technology. Nor have fluid lenses been manufactured in any desired shape other than a round shape because of complications introduced in non-uniform expansion of non-round fluid lenses. It is therefore desirable to provide solutions to these limitations so commercialization becomes feasible.

## BRIEF SUMMARY

[0005] The limitations of previously-available fluid-filled lens technology described in the background section above may be removed by constructing a fluid lens as described herein. Fluid lenses disclosed in the prior art have frequently been round lenses because it is difficult to manufacture a non-round fluid lens that is free of optical aberrations. Some prior art fluid-filled lenses use aspheric front lenses to correct for optical aberrations induced by the inflation of a membrane when it is of a non-round shape. Because this correction can be made for only one particular shape of the membrane corresponding to one particular degree of inflation, adjusting the optical properties of the front lens alone is not sufficient to fully correct the problem.

[0006] Some fluid-filled lenses use contoured membranes having different thicknesses at different points on the optic in order to reduce optical aberrations (mainly astigmatism) in

the fluid lens. Embodiments of the present invention include an improved contoured membrane design derived from a design optimization methodology that combines optical image analysis with use of finite element software to compute mechanical deflection of the membrane in response to a particular hydrostatic pressure created in the fluid layer.

[0007] In one embodiment of the present invention, a fluid lens includes a front lens, a membrane, and a fluid layer therebetween, with the front lens configured to compensate for any astigmatism that develops in said fluid lens upon inflation of the membrane.

In certain embodiments, the membrane includes thickness contours, with at least one contour within an optical zone of said fluid lens. In other embodiments, the front lens is configured to compensate to cancel out any asphericity of the membrane at a particular stage of inflation of the membrane. The particular stage of inflation can be for example within an overall range of desired power, or at one-third of full inflation of the membrane.

[0008] Further embodiments, features, and advantages of the present invention, as well as the structure and operation of the various embodiments of the present invention, are described in detail below with reference to the accompanying drawings.

## BRIEF DESCRIPTION OF THE DRAWINGS/FIGURES

[0009] The accompanying drawings, which are incorporated herein and form a part of the specification, illustrate the present invention and, together with the description, further serve to explain the principles of the invention and to enable a person skilled in the pertinent art to make and use the invention.

[0010] FIG. 1 shows a front view of a portion of a lens according to a first embodiment of the invention.

- [0011] FIG. 2 is a chart showing spherical power value along x and y axes for the embodiment of FIG. 1.
- [0012] FIG. 3A shows a front view of a lens according to another embodiment of the invention.
- [0013] FIG. 3B shows thickness profiles in the y and x directions of the embodiment of FIG. 3A.
- [0014] FIG. 3C is a chart showing the retinal image quality as a function of gaze angle in the horizontal direction for the embodiment of FIG. 3A.
- [0015] FIG. 3D is a chart showing the retinal image quality as a function of gaze angle in the vertical direction for the embodiment of FIG. 3A.
- [0016] FIG. 4A shows a front view of a lens according to another embodiment of the invention.
- [0017] FIG. 4B shows additional views of the embodiment shown in Figure 4A.
- [0018] FIG. 4C shows two charts showing surface optical properties of the embodiment of FIG. 4A along the x and y axes.
- [0019] FIG. 4D shows two charts showing astigmatism values of the embodiment of FIG. 4A along the x and y axes
- [0020] FIG. 4E is a chart showing retinal spot size for the embodiment of FIG. 4A.
- [0021] FIG. 5 is a flowchart showing a method of designing a lens according to an embodiment of the invention.
- [0022] The present invention will be described with reference to the accompanying drawings.

## DETAILED DESCRIPTION

[0023] While specific configurations and arrangements are discussed, it should be understood that this is done for illustrative purposes only. A person skilled in the pertinent art will recognize that other configurations and arrangements can be used without departing from the spirit and scope of the present invention. It will be apparent to a person skilled in the pertinent art that this invention can also be employed in a variety of other applications.

[0024] It is noted that references in the specification to "one embodiment," "an embodiment," "an example embodiment," etc., indicate that the embodiment described may include a particular feature, structure, or characteristic, but every embodiment may not necessarily include the particular feature, structure, or characteristic. Moreover, such phrases are not necessarily referring to the same embodiment. Further, when a particular feature, structure or characteristic is described in connection with an embodiment, it would be within the knowledge of one skilled in the art to effect such feature, structure or characteristic in connection with other embodiments whether or not explicitly described.

[0025] Throughout this disclosure, the term fluid lens assembly will be used to describe the assembly of a rigid front lens, a flexible membrane and an intervening fluid, while the term fluid lens will be used to denote the fluid layer and the two surfaces containing the fluid and forming the surfaces of the fluid lens. The term inflation is used herein to denote the curving outwards of the membrane when additional fluid is injected into the fluid lens assembly, causing the membrane to stretch out. As discussed herein, there is a direct and proportional relationship between the change in power of a fluid lens and the level of inflation effected. The term optical zone is used to denote a viewing zone in the fluid lens that is centered on an optic axis corresponding to the location of a user's eye. In

an exemplary embodiment, the optical zone is approximately 15 mm wide (along the x axis) and approximately 12 mm high (along the y axis), which corresponds to a horizontal gaze angle of about  $\pm 15$  degrees and a vertical gaze angle of about  $\pm 12$  degrees. The word contoured denotes variation in a mechanical dimension such as thickness, a mechanical property such as sag or an optical property such as astigmatism or power in the x, y plane.

[0026] The aspheric fluid lens provided herein includes a mostly rigid optical lens made of glass or plastic, or any other suitable material, a mostly flexible contoured membrane stretched over the edge of the front lens, and a fluid filling the cavity formed between the front lens and the flexible membrane. In an embodiment, this fluid lens is connected via a connecting tube to a reservoir including shaped elastomeric deformable membrane that contains excess fluid. The fluid lens, the connecting tube and the reservoir together form a sealed unit. Provision is made to squeeze the reservoir to push fluid out into the fluid lens through the connecting tube. For example, the provision to squeeze the reservoir may be in the form of a plunger impinging against a diaphragm to increase pressure within the reservoir, a caliper for squeezing the reservoir, or any other fluid pump or actuator known to one of skill in the art. An exemplary sealed unit is disclosed, for example, in U.S. Application No. 12/399,368, which is incorporated by reference herein in its entirety.

[0027] As discussed herein, embodiments of the present invention include an improved contoured membrane design derived from a design optimization method that combines optical image analysis with use of finite element software to compute mechanical deflection of the membrane in response to a particular hydrostatic pressure created in the fluid layer. This design method led to a series of membrane thickness contours that enable development of non-round fluid lenses.

[0028] Figure 1 shows a fluid-filled lens according to an embodiment of the present invention. Aspheric fluid lens 100 includes thick zone 110, hinge-like section 160, transition zone 140, and center disk area 120. In an embodiment, thick zone 110 has a thickness of approximately 1 mm, center disk area 120 has a thickness of approximately 0.225 mm and the thickness of transition zone 140 at disk edge 130 is approximately 0.1125 mm. In an embodiment, center disk area 120 has a diameter of approximately 12 mm, and disk edge 130 has a diameter of approximately 23.2 mm. A hinge-like section 160 is formed between thick zone 110 and transition zone 140. The dimensions of this exemplary embodiment provide for a 22 degree gaze angle between the center of center disk area 120 and disk edge 130. In an embodiment, frame 150 is a rounded rectangle, approximately 55 mm by 25 mm in size. This configuration provides for the best optical performance in center disk area 120 while maintaining acceptable properties to the edge of frame 150.

[0029] Analysis of the membrane inflation over a 2.00D power range shows that while the magnitude of inflation of the membrane decreases with increased thickness of lens 100, the membrane surface becomes increasingly aspheric, building up astigmatism. Figure 2 shows the spherical power of the above embodiment at low inflation pressure (8 mbar) along x and y axes, which demonstrates this divergence.

[0030] Figures 3A-3B show a lens 300 according to another embodiment of the present invention, including a contoured design of thickness of membrane 350. Aspheric fluid lens 300 includes thick zone 310, center disk area 320, and disk edge 330. Transition zone 340 is formed between disk edge 330 and center disk area 320. Hinge-like section 360 is located between disk edge 330 and thick zone 310. In an embodiment, center disk area

320, transition zone 340, hinge-like section 360, and disk edge 330 are in the shape of ellipses.

[0031] Figure 3B in particular shows thickness profiles of lens 300 in the y (shown on the left side of FIG. 3B) and x (shown on the right side of FIG. 3B) directions. The purpose of hinge-like section 360 is to allow full inflation of membrane 350 corresponding to the target power range, and yet minimize stresses transferred to peripheral less-flexible thick zone 310 that would cause astigmatism to build. From one perspective, hinge-like section 360 allows sag changes to be “absorbed” without causing optical distortion in both central optical zone within center disk area 320 and peripheral less-flexible thick zone 310 portions of membrane 350.

[0032] In an embodiment, central optical zone within center disk area 320 in membrane 350 has a degree of eccentricity of about 0.9. That is, the horizontal width is about 1.11 times bigger than the vertical width. This design pushes the location of the transition zone corresponding to hinge-like section 360 to greater gaze angles in the horizontal direction, where it places lesser constraints upon visual width and horizontal eye movements. In an embodiment, a vertical cross-section thickness is approximately 0.200 mm, a width is approximately 3.7 mm, and an aspect ratio is approximately 1:18.5. In an embodiment, the horizontal cross-section thickness is approximately 0.2 mm, with a corresponding width of approximately 1.45 mm, and an aspect ratio of approximately 1:7.

[0033] The use of a hinge section (e.g., hinge-like section 360) which acts as a transition zone makes it possible to effectively isolate optical properties of a membrane (e.g., membrane 350) within individual sections, at a cost of developing an image jump at the hinge section. A hinge having a high aspect ratio, defined as the ratio of the width to its thickness, is particularly effective. In an embodiment, the width is in the range of 0.1 mm

to 2.5 mm. In a further embodiment, the range of thickness of the hinge section is 0.01 mm to 0.25 mm. In a still further embodiment, the range of thickness of the hinge section is 0.07 mm to 0.20 mm. For gaze angles that are generally used for near vision (e.g., approximately 0-15 degrees), this configuration will provide for target image quality (e.g., approximately 10 microns, corresponding to approximately 0.5D of astigmatism, or approximately an equivalent 0.25D of image blur).

[0034] Figure 3C is a chart that shows the retinal image quality as a function of gaze angle in the horizontal direction for this embodiment. Figure 3D is a chart that shows the retinal image quality in the vertical direction for this embodiment. As shown therein, image quality, as a function of spot radius, decreases as the distance from the optical axis increases.

[0035] Figure 4A shows another embodiment of the present invention including a lens 400 having a membrane that uses a partial hinge. Forming a hinge of proper aspect ratio that encompasses the entire optical zone may entail manufacturing challenges. To account for this, the embodiment shown in Figure 4A includes partial hinge 410, which is provided much closer to the frame edge relative to the embodiment shown in Figure 3A. A partial hinge (e.g., partial hinge 410) has a dual advantage over the hinge design of the embodiment shown in Figure 3A. The first advantage is that it is easier to mold because it is closer to the edge and is partial in length, rather than a continuous section surrounding the optical zone. The second advantage is that any optical distortion associated with the hinge (such as, for example an image jump) occurs much closer to the frame and is less noticeable by the wearer.

[0036] Figure 4B shows additional views of the embodiment shown in Figure 4A, including a front view and cross-sectional views of lens 400.

[0037] Figure 4C is a chart showing a MATLAB analysis of the surface optical properties of the membrane of the embodiment of Figure 4A, specifically, the power along x and y axes. These results were obtained using polynomials to fit a model having a central elliptical portion whose radius along the x-axis is 13 mm, and radius along the y-axis is 8 mm.

[0038] Figure 4D is a chart showing a MATLAB analysis of astigmatism along x and y axes of the embodiment of Figure 4A. These results were obtained by applying compensation to the front lens corresponding to the asphericity that develops in the membrane when inflated to one-third of the full range. The compensation is applied simply as a subtraction of sagittal values because the refractive indices are closely similar, and the lens may be modeled as a thin lens. These analyses were performed using extended polynomials to fit an elliptical region covering the central optical zone. The modeled ellipse has a radius of 13 mm on the x-axis and 8 mm on the y-axis, and covers an area of 52 degrees by 32 degrees.

[0039] Figure 4E is a chart showing retinal-spot size for the membrane of the embodiment of Figure 4A working with a compensated front lens. Image quality analysis was performed on ZEMAX for this geometry in association with a compensated front lens. This chart represents a situation with equal correction on both front lens surfaces (null lens). It shows that the astigmatism and other optical aberrations causing a broadening of the retinal spot is maintained under control and less than approximately 0.5D of astigmatism (equivalent to approximately 0.25D of image blur) for gaze angles of up to 10 degrees at both horizontal and vertical directions. This analysis was performed using a grid sag representation covering the full membrane.

## Method and Experimental Results

[0040] Figure 5 is a flowchart showing a method of designing a lens according to an embodiment of the invention.

[0041] First, in step 510, a membrane is defined as having an edge constrained by the edge of the front lens to which it is bonded. Therefore, when the membrane is inflated by increasing hydrostatic pressure of the fluid, the surface of the membrane acquires an aspheric shape. In an experimental embodiment performed by the inventors, this shape was modeled and predicted using a finite element software package such as COMSOL.

[0042] Next, in step 520, in order to predict the inflation of the membrane, the front lens is given a simple geometry for this computation, such as a spherical geometry. In an experimental embodiment performed by the inventors, a front lens of zero power in which both surfaces were spherical was used.

[0043] In step 530, the membrane surface is calculated as a function of inflation for one or more of the following parameters: shape of the edge of the front lens, membrane thickness profile, level of inflation, and hydrostatic pressure. In an embodiment, a finite element software program can be used to calculate the membrane surface. In an experimental embodiment performed by the inventors, COMSOL was used.

[0044] In step 540, the aspheric surface is analyzed by fitting it to a polynomial or a set of polynomials in order to calculate the surface spherical power and astigmatism for the optical zone at all locations on the membrane surface from its local curvatures. In an experimental embodiment performed by the inventors, this analysis was carried out using the commercially available software package MATLAB. In step 550, the membrane thickness contours can be varied and the same computation performed, repeating the process until an acceptable contour (distribution in x, y plane) of spherical power and

astigmatism has been achieved. Power, as used herein, means spherical power or average spherical power, and is measured as  $\frac{1}{2}[\partial^2/\partial x^2(C_{x,y}) + \partial^2/\partial y^2(C_{x,y})]$ . Acceptable contours of power and astigmatism of the membrane surface are deduced from both experience and the desired optical performance at various levels of the power range of the fluid lens assembly being targeted.

[0045] Next, in step 560, the front lens is modified to compensate for effects due to the asphericity of the membrane. This compensation can be carried out at any level of inflation. For the special case when the refractive index of the fluid is approximately equal to the refractive index of the front lens material, this compensation can be reduced to a point-by-point subtraction of membrane sagittal thickness from the front lens. In an experimental embodiment performed by the inventors, further modeling work on COMSOL showed that the departure from a spherical shape was relatively linear with the level of inflation at moderate levels of inflation for the membrane, indicating that if the compensation process is carried out at an inflation level corresponding to the midpoint of the desired range of optical powers of the fluid lens, it would be possible to achieve a symmetrical change in optical performance of the fluid lens through the overall range of powers, being worst at the lowest and highest end points of the power range.

[0046] The compensation will be the lowest if carried out at the lowest end of the power range, and maximum if carried out at the highest end of the power range because the asphericity of the membrane surface increases with the level of inflation. In an experimental embodiment performed by the inventors, this compensation process was initially performed at the midpoint of the power range. Subsequently, this compensation process was performed at 33% inflation level, corresponding to an increase in power equal to 33% of the full range. The selection of the power level at which compensation is

applied depends on the desired relative quality of the fluid lens at various points of its power range.

[0047] It should be noted that the compensation may alternatively be carried out by adjusting either one or both surfaces of the front lens. However, the contribution of the back surface of the front lens to the optical properties of the fluid lens is dependent on the difference in refractive indices of the front lens material and the fluid. In cases where they are closely similar, the front surface alone can be used for modification in order to provide compensation. This has the advantage of reducing tooling time and cost. Use of the same correction on both surfaces (null lens) allows for uniform front thickness over the full range. It should also be noted that this correction adds to aspheric corrections made in order to compensate gaze angle induced cylinder.

[0048] Once the compensation has been computed as described above, in step 570, the optical properties of the fluid lens at all points of its power range is analyzed. In an experimental embodiment performed by the inventors, ZEMAX, which is a commercially available software package, was used for this purpose. For the special case where the refractive index of the front lens is approximately equal to the refractive index of the fluid which is also equal to the refractive index of the membrane material, it is possible to reduce the front lens to one refracting surface, treat the membrane as the second surface, and use the common refractive index and the overall sagittal thickness to set up the lens to be modeled. In an experimental embodiment performed by the inventors, the front lens was treated as a separate entity, allowing for different refractive indices for the front lens and the fluid. Retinal image quality was calculated using an eye model, and expressed as image-spot size. It was calculated along selected meridians of the fluid lens and for a range of gaze angles.

[0049] This whole process with several iterative steps built in may be termed a design tool chain to efficiently optimize the thickness contours of the membrane in order to achieve the best image quality. In an experimental embodiment performed by the inventors, because a set of three software packages were used to perform the computation of inflation and optical properties of the lens, efficient methods were developed to export data from one software package to the next, eventually automating this data transfer process, and performing optimization at intermediate points. It is desirable to provide for the efficient exporting of data from one software package to another, development of mathematical simulations of surfaces for efficient operation of the FEM and the ray tracing analyses programs, and creation of a merit function that defines the allowable level of astigmatic or other forms of image aberration as a function of gaze angle along specific meridians.

[0050] Another design element involves the relative magnitudes of refractive indices of the various optical elements involved in the fluid lens, the front lens, the fluid and the membrane. Of these, the refractive index of the membrane does not significantly affect the power of the fluid lens, but it has an effect on the visibility and cosmetics of the thickness contours that may be added to the membrane, as well as internal reflection from the inner surface of the membrane. These two undesirable features were minimized in an experimental embodiment performed by the inventors by ensuring that the refractive index of the membrane material was approximately equal to the refractive index of the oil, especially at the sodium D line of the spectrum. In an embodiment, a difference of 0.02 units or less may be used. In an embodiment, the refractive index of the fluid should be as high as possible in order to minimize the magnitude of inflation required to achieve a certain increase in optical power. In an experimental embodiment performed by the

inventors, the refractive index of the front lens was matched to the refractive index of the fluid to neutralize the optical contribution of the inner surface of the front lens and make the design simpler and more robust.

[0051] The foregoing non-limiting examples demonstrate the use of the design tool chain in creating and optimizing membrane geometry for a particular frame shape and a desired range of power that needs to be covered by the fluid lens assembly.

[0052] While various embodiments of the present invention have been described above, it should be understood that they have been presented by way of example only, and not limitation. It will be apparent to persons skilled in the relevant art that various changes in form and detail can be made therein without departing from the spirit and scope of the invention. Thus, the breadth and scope of the present invention should not be limited by any of the above-described exemplary embodiments, but should be defined only in accordance with the following claims and their equivalents.

[0053] Further, the purpose of the foregoing Abstract is to enable the U.S. Patent and Trademark Office and the public generally, and especially the scientists, engineers and practitioners in the art who are not familiar with patent or legal terms or phraseology, to determine quickly from a cursory inspection the nature and essence of the technical disclosure of the application. The Abstract is not intended to be limiting as to the scope of the present invention in any way.

## WHAT IS CLAIMED IS:

1. A fluid lens assembly, comprising:

a front rigid lens;

a semi-flexible membrane; and

a fluid layer therebetween,

wherein the front lens is configured to compensate for an astigmatism that develops in the fluid lens assembly upon inflation of the membrane, and

wherein the membrane includes thickness contours, and wherein at least one such contour is within an optical zone of the fluid lens assembly.

2. The fluid lens assembly of claim 1, wherein the front lens is configured to substantially cancel out an asphericity of the membrane at a particular stage of inflation of the membrane, wherein the particular stage of inflation is within an overall range of desired power.
3. The fluid lens assembly of claim 2, wherein the particular stage of inflation is at one third of full inflation of the membrane.
4. The fluid lens assembly of claim 2, wherein the membrane includes a hinge section having a thickness in the range of 0.01 mm to 0.35 mm.
5. The fluid lens assembly of claim 4, wherein the hinge section has a thickness in the range of 0.07 mm to 0.25 mm.

6. The fluid lens assembly of claim 2, wherein the membrane includes a hinge section having an aspect ratio in the range of 2.0 to 100.0.
7. The fluid lens assembly of claim 6, wherein the hinge section has an aspect ratio between 3.0 and 30.0.
8. The fluid lens assembly of claim 2, wherein the thickness of the membrane increases along the x axis towards the distal end of the fluid lens.
9. The fluid lens assembly of claim 1, wherein the front lens has a refractive index within 0.02 units of the refractive index of the fluid.
10. The fluid lens assembly of claim 1, wherein the membrane has a refractive index within 0.02 units of the refractive index of the fluid.
11. The fluid lens assembly of claim 1, wherein the membrane includes a plurality of hinge-like sections.
12. The fluid lens assembly of claim 12, wherein the plurality of hinge-like sections includes two horizontally aligned sections and two vertically aligned sections.
13. A corrective eyepiece comprising two fluid lens assemblies, each fluid lens assembly comprising:  
  
a front rigid lens;  
  
a semi-flexible membrane; and  
  
a fluid layer therebetween,

wherein the front lens is configured to compensate for an astigmatism that develops in the fluid lens assembly upon inflation of the membrane, and

wherein the membrane includes thickness contours, and wherein at least one such contour is within an optical zone of the fluid lens assembly.

14. The fluid lens of claim 13, wherein the front lens is configured to substantially cancel out an asphericity of the membrane at a particular stage of inflation of the membrane, wherein the particular stage of inflation is within an overall range of desired power.
15. The fluid lens of claim 14, wherein the particular stage of inflation is at one third of full inflation of the membrane.
16. The fluid lens of claim 14, wherein the membrane includes a hinge section having a thickness in the range of 0.01 mm to 0.35 mm.
17. The fluid lens of claim 16, wherein the hinge section has a thickness in the range of 0.07 mm to 0.25 mm.
18. The fluid lens of claim 14, wherein the membrane includes a hinge section having an aspect ratio in the range of 2.0 to 100.0.
19. The fluid lens of claim 18, wherein the hinge section has an aspect ratio between 3.0 and 30.0.
20. The fluid lens of claim 14, wherein the thickness of the membrane increases along the x axis towards the distal end of the fluid lens.
21. The fluid lens of claim 13, wherein the membrane includes a plurality of hinge-like sections.