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Adjustable fluidic lenses for ophthalmic corrections

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Abstract

We report on two fluidic lenses that have been developed for ophthalmic applications. The lenses use a circular aperture to demonstrate optical powers between -20 and $+20$ D and a rectangular aperture to demonstrate astigmatism with values ranging from 0 to 8 D. Measurements of image quality were made with the fluidic lens using a model eye. Both lenses were variable and controllable by adjusting the fluid volume of the lens. To the best of our knowledge this is the first demonstration of a continuously variable lens for control of astigmatism.

Adjustable fluidic lenses can provide a variable change in the optical wavefront of the light that passes through them [1–3]. This is accomplished by varying the fluidic volume in the lens, which causes a change in curvature of an elastic membrane. Several groups have investigated fluidic lenses to provide telescopes with adjustable zoom and field of view [4,5]. These telescopic devices alleviate the need for mechanically moving optical components, which reduces the overall size and weight of the telescope. Concentrating on variable telescopic applications has caused these groups to emphasize fluidic lenses with short focal lengths to obtain larger ranges of zoom and field of view. The work in this manuscript has concentrated on ophthalmic applications, which require longer focal lengths. The minimum focal length of ± 50 mm corresponds to a ± 20 D correction, which in ophthalmic applications would typically be considered an absolute bound on the desired range of interest, with most applications falling in the range ± 4 D.

Eye-care providers typically utilize a phoropter to aid in the determination of eyeglass prescription. Patients sit behind the bulky phoropter and view a distant eye chart. Different lens combinations in steps of 0.25 D are mechanically switched into the patient's line of sight. The powers are systematically adjusted until the patient selects the set of lenses that gives him or her the clearest vision of the chart. The lens combination is then transcribed to the patient's eyeglass prescription. Using fluidic lenses for the phoropter allows the development of an instrument that can continuously vary the wavefront of light to mechanically circumvent changing lenses. This instrument could be constructed in a much smaller size, which would be less intrusive to the patient. Also, the examination time could also be reduced, since changing the wavefront could be computer controlled, which would allow a higher patient throughput.

The fluidic lenses discussed in this manuscript are composed of a polydimethylsiloxane (PDMS) membrane, which is elastic. The lens chamber fluid volume is altered to stretch the PDMS in either a concave or a convex manner. This control of the curvature of the PDMS surface can then be used to cause a change in the optical wavefront in a controlled manner. Two types of lenses have been investigated. The first lens utilizes a circular restraint of the PDMS membrane to provide changes in the spherical power of the lens. The second fluidic lens uses a rectangular restraint to provide varying amounts of cylindrical power. Using combinations of these lenses would allow a complete eyeglass prescription to be obtained by determining spherical, cylindrical, and angle components of the prescription for both eyes. A combination of two fluidic cylindrical lenses with axes oriented at 45° with respect to one another can create an arbitrary level and orientation of cylindrical power.

The PDMS membrane was fabricated using a commercially available product that was obtained from Dow Corning (Sylgard 184). The PDMS was mixed with its curing agent in a 10:1 ratio and then poured into a mold that contained a 50-mm-diameter glass plate at the bottom of the mold. The side of the PDMS that was formed against glass surface then became the optical front of the lens because of its smooth surface. Next, the PDMS was placed in a desiccator and a vacuum was pulled on the PDMS film to remove any residual gas bubbles that were induced during the mixing process. The membrane was baked at 65°C for 4 h to reduce the curing time of the PDMS membrane. The membrane was then removed from the mold, and the membrane thickness was measured to be approximately 700 µm. This thickness is thicker than other reports [1,3,5] in the range of 30 to 120 µm; however, the thicker membrane facilitated the lower curvatures sought in this research. The membrane was then mounted in the mechanical holder and care was taken to assure uniform alignment of the membrane.

The mechanical holder is composed of three parts and is shown in Fig. 1. The bottom part of the holder provided the mechanical mounting of an optical glass (Edmund Optics NT45-642), which was sealed using a standard O-ring. A 2.54-cm-diameter (1 in.) aperture was machined to allow light through. The middle portion of the holder is the fluidic chamber. It contains two tapped holes, one for connection to a dual syringe and one to allow the escape of air during the filling of the chamber. The dual-syringe system was used so that one syringe could be used for making large changes in the fluid volume, while the smaller syringe was used to provide precise volumetric changes. The top portion of the cell was used to mount and secure the PDMS membrane. The edge of the aperture was beveled so that the membrane would maintain a minimum amount of tension to avoid unwanted ripples. Two separate interchangeable apertures were fabricated. The circular aperture had a diameter of 2.54 cm, while the rectangular aperture had dimensions of 3 cm X 1.5 cm.

The surface of the PDMS was characterized using a Wyko NT 9800 optical profiler (Veeco), which is a white-light interferometer. The profiler was operated in the vertical-scanning interferometer mode. The instrument acquires two-dimensional images and scans vertically. The fringe visibility of a low coherence source is used to determine the surface profile for each image. The optical profiler field of view was maximized for our instrument using the smallest field lens of 0.55X and the smallest magnification objective of 5X. This resulted in a full field of view of approximately 2 mm. The surface profile was realized with twelve images taken in a 3 X 4 pattern and stitched together to produce a 5-mm-diameter image. Surface-profile measurements were taken, and then the fluid volume was adjusted using the smaller syringe. Orthogonal line scans (Fig. 2) are plotted for optical powers of 0, 0.25, 0.5, 0.75, 1.0, and 2.0 D. The optical power was determined from the surface curvature, coupled with the index of refraction of the PDMS, which was estimated to be 1.42 [6], and the index of refraction for the deionized water was 1.33 [7]. The mounting glass was also included in the calculations but provided negligible changes in optical power. Slight waveform distortions are present and have been attributed to membrane misalignment. However, these distortions produce optical peak-

to-valley wavefront errors of less than 0.3 waves at 550 nm, which should be unperceivable to the human eye.

The astigmatic lens was also measured using the 5X objective and the 0.55X field of view. Six images were taken in a 2 X 3 pattern and stitched together to produce a 4.2 mm square profile for the surface of the PDMS (Fig 3). The rectangular aperture produces a combination of cylindrical and spherical components for the lens. The measured lens curvature was used to extract both the cylindrical and spherical components produced by the lens. In the actual device, the spherical component could be nullified using the lens with the circular aperture.

A subjective image quality was obtained by using a model eye and a two-dimensional picture of a small child as an object. The model eye (Fig. 4) is composed of fluidic chamber, which is filled with saline solution. An intraocular lens with an optical power of approximately 20 D is inserted in the chamber. Next, a 6 mm pupil is inserted into the eye, and this became the system pupil. A 40 D lens is then used to approximate the cornea. Then a thin ophthalmic trial lens is inserted to produce the aberrated eye. The fluidic lens is placed after the model eye. The pupil in the eye produces a footprint of approximately 7.6 mm on the PDMS membrane. With the field of view performed in this test, approximately 10.6 mm of the membrane is examined in the images. While testing the fluidic lens with a rectangular aperture, another ophthalmic trial lens was used to correct the spherical component of the optical power. In the future, a separate fluidic lens with a circular aperture would be used to adjust the spherical power.

Images were recorded (Fig. 5) with a digital camera. Initially, the fluid volume of the astigmatic lens was adjusted until there was no observable astigmatism remaining. Changing the fluid volume in the astigmatic lens changes both the power and astigmatism components of the lens. The corrected image of the child can be seen (Fig. 5) for a 2.0 D correction. Images were taken progressively up to 8 D of correction with similar results for the corrected image. Similarly, images were taken with the circular restraint to correct images for optical power ranging from +20 D to -20 D. An example of the image correction is shown (Fig. 5) for 2 D of optical power.

An image through the model eye without the fluidic lens was taken [Fig. 5(c)] for comparison purposes. Also, an image was taken through the fluid lens when the optical power was adjusted to 0 D. This demonstration is quite critical for our applications and required a thicker PDMS layer along with careful mounting of the membrane. We have not seen any reports of zero power from a fluidic lens in the literature.

In summary, we have presented a fluidic lens that is designed for ophthalmic applications. Two types of lenses were demonstrated. The first lens was designed to provide spherical powers in the range of ± 20 D and demonstrated the ability to go from positive to negative power. The second lens was used to generate cylindrical power. The lenses were shown to correct defocus and astigmatism to obtain a clear image for a broad range of refractive errors. We envision that the optical power of the lenses could be controlled using either pressure or change in fluidic volume. The lens design is small and compact, which potentially eliminates the need for mechanically moving or changing lenses in a phoropter.

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Fig. 1. Cell mount for the fluidic lens. The top plate is shown with a rectangular mount (astigmatism) for the PDMS membrane. A second, interchangeable plate with a circular mount was used to create defocus. See the text for discussion.

Fig. 2. Line scans of the wavefront surface profiles for the fluidic lens with a circular mounting aperture. The scans were taken at 0, 0.25, 0.5, 0.75, 1.0, and 2.0 D.

Fig. 3.

Wyko profile of astigmatic lens with (a) 2.69 D of cylinder at 90° with -1.66 D of optical power, (b) 0.35 D of cylinder at 85° with -0.81 D of optical power, and (c) 2.11 D of cylinder at 1.3° with 1.85 D of optical power. The reference point for each of the lens surface profiles was chosen to be at the center of the image. The surface profiles were measured over a 4.2-mm-diameter area.

Fluidic Lens

Model Eye

Fig. 4.

Schematic of the imaging system that is composed of a model eye and the fluidic lens. The details of the system are discussed in the manuscript.

Fig. 5.

Images taken through the cylindrical glass lens when (a) the fluidic lens has no power and (b) the fluidic lens is adjusted to correct for the 2.0 D of astigmatism induced in image. For comparison, images taken (c) without the fluidic and spherical glass lens and (d) with just the circular fluidic lens at no power. Also shown are images taken through a spherical lens when (e) the fluidic lens has no power and (f) the fluidic lens is adjusted to correct for 3.0 D of optical power.