Adaptive liquid Filled Membrane Lens

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Abstract: Adaptive optics control using liquid filled membrane lens is based on the principle of deflection of polymeric membrane. Controlled deflection in membrane leads to controlled focal length. This enhances the focus tuning ability of the system at the same time make optical system compact and economical. The adjustment of fluid pressure helps to toggle between different field of view at the same time maintaining optimum illumination for each field of view. This system has applications in miniature optics. Some of identified areas include three-dimensional biomedical imaging, optical coherent tomography, target identification in tactical applications in infrared region, and telescope. This paper describes the simulation of liquid filled membrane lens and focusing using fluid pressure regulation.

Keywords: Adaptive, Optofluid, Pressure, Tension

1. Introduction

Adaptive optics is a whole new era and is the need of the hour as they are proving to be more versatile, efficient and have much faster response time than conventional arrangement of lenses. Earlier developments in this field have so far been successful since the first patent in this field was filed in the 1940's. Recently a response time of around 2ms was reported using a liquid–liquid interface [1]. The basic principle behind this phenomenon is to distort the interfacial surface of the two liquids so as to get a variable focal length which is the function of applied pressure. Usually in most of the cases the fluid is confined within the membrane and with the application of the pressure the membrane stretches, hence changing the focal length. Medical imaging has vast applications and Kang et al. [4] discussed its application in endoscopic based imaging techniques.

In recent years the principle of pneumatic based deformable lens has also been further experimented on an array of such lenses in MEMS using an optofluidic network [5-6]. This variable focal length micro lens can be actuated by various means such as using an electromagnet [3], piezoelectric based or dielectric based elastomer actuators. Usually there is a need of such a material for the membrane which does not show permanent deformation when the pressure is released and hence should also have a low Young's modulus withstanding large deformation and one such material favorable for these conditions is polydimethylsiloxane (PDMS) [3]. McDonald et al. [2] studied the feasibility of PDMS in MEMS and hence concluded the effectiveness of this material to be used as a component in variable lens system.

The pressure being applied to deform the lens can be pneumatic based or by any other means of using another liquid to create pressure within the chamber can be used. Apart from PDMS other types of silicon membranes can also be used in the fabrication of tunable adaptive lenses, Schneider et al. [7] studied the piezoelectric based actuation of a liquid lens confined in a silicon membrane.

In liquid filled lenses liquid inside lens membrane play important role and affects the performance of the lens, there the requirements of liquid is in terms of transmission, operational brodband, high refractive index, chemical reactivity, viscosity, evaporation, low density to decrease the gravitational effect. For assembly the sealant material should be selected carefully, It should not react with fluid and membrane to bond membrane firmly and tightly with frame, oxygen plasma bonding technology is often recommended [10]

Various application is described in micro fluidic channel [9, 8, 13], Intraoral scanners [15], Tunable opto fluidic silicon optical bench [16,17], a similar kind of deformation control can be obtained using electrowetting principle and used in electro wetting display [18].

This paper describes the basic relation for theoretical evolution of deformation and simulation of the PDMS membrane deflection using solid mechanics, the deflection is obtained for various pressure, the pressure selection is based on deviation from spherical geometry, paper shows difference between glass and membrane lens in terms of deformation.

Table 1. Geometric dimensions and material properties

Physical Quantity	**Value**
Diameter	15mm
Thickness	0.5mm
Refractive index	1.5
Tensile strength	2.24MPa
Young's Modulus	360-370MPa
Poisson Ratio	0.5
Transmission	400-900nm(100um thick)

2. Mathematical Modeling

For simplifying the problem in mathematical modeling a circular PDMS thin membrane was considered. This membrane was fixed by slicing the membrane between the holder, hence fixed constraint we applied at the thin circular region and over the circumference at the edge. A differential pressure across the transmission face is assumed to be constant. This model was solved in solid mechanics based physics in using Comsol Multiphysics, the model was solved for steady state solution. Figure 1 shows the model geometry of the mathematical model along with boundary condition.

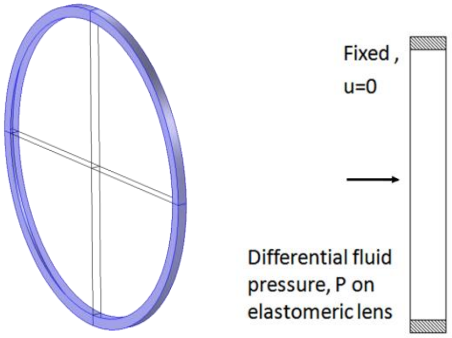

Figure 1. Geometry and boundary condition of the membrane.

3. Equations

Theoretically the model can be solved using set of equations representing the relation between coordinates, pressure and elastic constant in equation, Using the theoretical explanation given by Sugiura [8] and Knolllman [14], the lens surface deformation can be evaluated using force balance.

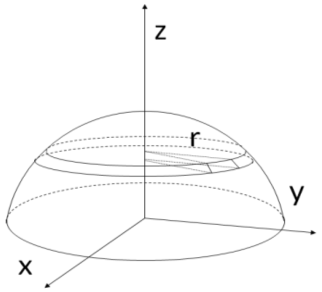

Figure 2. Deflected membrane geometry.

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial z}{\partial r}\right)=-\frac{P}{S}$$

the solution of differential equation parabolic relation between z and r

$$z=-\frac{P}{4S}(a^2-r^2)$$

According to Sugiura's derivation [8]

$$z=-\frac{\rho g a}{S}\left(\left(y^2-\frac{y^3}{6a}-\frac{4}{3}ay\right)+k\left(y^2-2ay\right)\right)$$

$$k=\frac{P}{2\rho g a}$$

when k is high (k>30), th gravity effect effect is is negligible and surface becomes parabolic.

$$k=\frac{P_o+\frac{2S}{R}}{2\rho g a}$$

Laplace pressure defines the relation between inside and outside pressure and is related to elastic constant of the membrane and radius of curvature [11]

$$P=P_o+\frac{2S}{R}$$

Maximum error in displacement according to Knollman's analysis, is given by

$$\Delta z_{\max}<h\left(\frac{h}{2a}\right)^2, h<<2a$$

For small aperture if displacement is such that $z_{\max}$ <.1um (Very small value lies in the tolerance of surface roughness or form error of spherical glass lens).

The model explained in Figure 1 was solved assuming displacement and velocity field zero initially, fixed constrains were applied at the edge at the top, bottom (u=0) and annular region of face. Differential pressure P (shown in Figure 2) was applied across the two faces.

Fixed Constraint
$\mathbf{u}=0$
Boundary load
$\sigma.\mathbf{n}=\mathbf{F}_A, \mathbf{F}_A=-p\mathbf{n}$

4. Results

Based on theoretical evaluation the range of applied differential pressure was selected as shown in Figure 3. Total displacement at various pressure is indicated in this figure, the displacement increases with increase in the applied pressure but at the same time deviation from spherical behavior increases at high pressure and at high pressure the displacement is parabolic in nature.

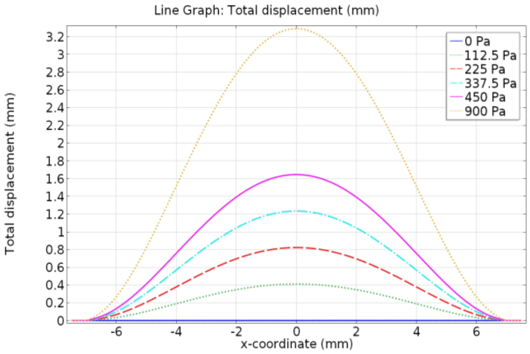

Figure 3. Deflection in PDMS membrane.

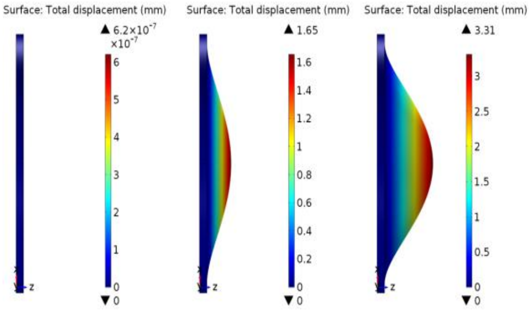

Figure 4. Deflection in lens at 0 Pa(left) 450Pa (middle) 900Pa (right).

Figure 4, shows the displacement contour from no deflection state to maximum deflection within assumed pressure range.

Deviation from the designed surface leads to enhanced optical aberrations, this is also sometime called as wave front error, the geometric comparison was done with equivalent glass lens and lens formed after deflection at low pressure, Figure 5 shows the Membrane lens profile, glass lens profile and difference between these two profiles.

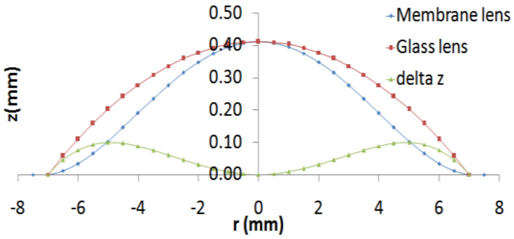

Figure 5. Comparison in spherical glass and membrane lens(112.5Pa).

5. Conclusions

Fluid pressure variation changes the displacement in the membrane thereby changing the lens power, this makes the liquid filled membrane lens adaptive but there is some associated uneven deformation in comparison with spherical lens. At high pressure the surface becomes parabolic which may be even or uneven according to design requirement, this deformation may be controlled using the suitable geometry, fixing lens at certain predefined angle for enhancing sensitivity in a particular range of optical power. Apart from there are other challenges in terms of stability and gravitational effect at relatively large apertures.

7. Nomenclature

Physical Quantity	Symbol
Radial distance	r (m)
Pressure	P (N/m^2)
Elastic Constant	S (N/m)
Density	ρ (kg/m^3)

radius	a (m)
height	h (m)

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