Comparison between liquid and solid tunable focus lenses

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Abstract. Nowadays more reports in the use of tunable lenses are reported, it is due to the benefits they offer in optical systems design. A tunable lens is an optical system that can focus on a range of positions by changing dynamically one of its geometric parameters. There are several types of tunable lenses, the most known types are the liquid, the solid elastic, with variable refractive index, and lenses that use a dielectric medium. This paper presents the analysis and opto-mechanical design of two tunable lenses, a liquid lens and another Solid Elastic Lens (SEL). Both lenses are made in mounting aluminium and polydimethylsiloxane (PDMS) as refractor medium, the liquid lens use two elastic membranes containing a liquid medium between them while the SEL only use PDMS material as body of the lens (medium refractor). We describe the opto-mechanical performance of both types of lens highlighting the main features of each. Finally, results of a opto-functional comparison between these prototypes are showed.

1. Introduction
In recent years there has been a considerable increase in the use of variable focal length lenses, especially as micro lenses in photographic objectives, endoscopes, microscope objectives, etc., a feature of these VFLS is that they always have a mechanism whereby the shape of the lens and its geometrical parameters can be changed; \cite{1, 2}, due to the possibility of making them lighter, simpler and more compact. There are different types of tuneable lenses: Tunable liquid lenses composed of a cylindrical metallic mount with a compartment for two transparent elastic surfaces filled with gas or liquid. By modifying the quantity of medium within the mount, the axial thickness and the curvature radii of the surfaces are changed \cite{3, 4}. There are micro lenses made from a dielectric liquid medium that changes its shape when an electric field is applied to it \cite{5}. There are also lenses that change their refraction index to produce changes in their geometrical parameters \cite{6}. In these types of tunable lenses requires a relatively high voltage approximate 100 V and constructing a large aperture electrowetting lens is challenging, or requires elaborated mechanical hydro-pneumatic system to produce tuning focus \cite{7, 8}.

Nowadays focused tunable liquid lenses are formed by a liquid medium and two flat elastic membranes \cite{9, 10}. A recent study, in which we used liquid lenses with variable focal length,
described the design, manufacture and the mechanical characterization of elastic membranes and components as well as their optical performance [11]. These elastic membranes are made from Sylgard 184 Silicone Elastomer [12]. In other work, we described the complete opto-mechanical design, manufacturing process, and the type of image that produce the solid elastic lens (SEL) elaborated of the same material [13].

In the present study; we will describe the opto-mechanical design of the proposed tunable lenses, one composed with two membranes in meniscus shape (we use meniscus with conic shape in order to improve the quality of the images) and the other solid elastic lens made of PDMS; we will study these type of lenses when radial stress is applied on its perimeter and when liquid pressure is applied respectively. Analysis of mechanical behavior of the membranes is presented. Finally, a theoretical analysis and simulations of the optical performance of the lenses proposed are shown.

2. Opto-mechanical Design of Tunable liquid lens

A tunable liquid lens is one that consists of a mechanical mount that contains a liquid refractor medium, two elastic membranes, a conduit to remove air from chamber, manometer, and a system to introduce and remove liquid of the chamber of the lens. The liquid pressure on the membranes surface causes that the thickness and curvatures change. A schematic diagram is shown in the figure 1.

![Figure 1. Schematic diagram of the tunable liquid lens.](image)

The mechanical mount is manufactured of aluminum and the membranes are made of Polidimethilsiloxane (PDMS) [14, 15]. In our proposal, the water is introduced to lens mount by the air/oil converter system, the water pressure onto the membranes is controlled with a pair valves. Unlike traditional designs of tunable liquid lenses, which employ membranes with plane surfaces [16]. Dein Shaw [17] proposed to use elastic membranes of meniscus type and spherical surfaces. We propose to use membranes with meniscus shape but with aspherical surfaces. To do it, we use the aspherical plane convex lens design by Kingslake [18], when the curved aspherical surface faces the distant object. By equating optical paths between any finite ray and the axis, we find

\[ Bn = X + n \left( \frac{B - X}{2} + X^2 \right)^{1/2} \]  

whence

\[ \frac{\left( X - \frac{Bn}{n(n+1)} \right)^2}{\left( \frac{Bn}{n(n+1)} \right)^2} + \frac{Y^2}{\frac{Bn}{n(n+1)}} = 1 \]
Where $n$ is the refraction index of the membrane elaborated of PDMS, $B$ is the back focal length, in our case $X$ is the thickness of the lens, $Y$ is the semidiameter of the lens and the conic constant is given as $K = -1/n^2$. We use two similar plane convex membranes to form the tunable meniscus lens. The initial geometric parameters of the lens without applied extra pressure onto the membranes are shown in the table 1, figure 2 shows a schematic diagram of the tunable liquid lens. To know the optical behavior of the proposed lens, the geometrical parameter was introduced in the OSLO™ optical design software (see table 1). For this, a trace ray was made; we considered that the object is at infinite. The effective focal length is 291.035mm.

| Curvature radius | Thickness | Aperture radius | Material | Conic constant |
|------------------|-----------|-----------------|----------|----------------|
| 241              | 0.5       | 15              | PDMS     | -1.988         |
| Plane            | 10        | 15              | Water    |                |
| Plane            | 0.5       | 15              | PDMS     | -1.988         |
| -241             |           | 15              |          |                |

Table 1. Geometrical parameters of the tunable liquid lens (the units are millimeters).

Figure 2. Schematic diagrams of the tunable liquid lens.

The figures 3 and 4 show the spot diagram and wavefront aberrations found in the tunable liquid lens without pressure applied on the membranes.

Figure 3. Wavefront aberrations found in the tunable liquid lens without pressure applied.  

Figure 4. Spot diagram produce by tunable liquid lens without pressure applied.
The values of the aberrations found in the tunable liquid lens without pressure applied are shown in the table 2, where we can see that the spherical aberrations is minimum to points on axes, \( \lambda = 632.8 \) nm was the wavelength employed to do calculations.

| Spherical | Coma     | Astigmatism | Petzval | Distortion |
|-----------|----------|--------------|---------|------------|
| -0.021335 | 5.0476e-07 | -7.4231e-12 | -5.3307e-12 | 6.0785e-18 |

In the next section, we describe the optical design of the solid elastic lens without forces applied on the border by the mechanical mount.

3. Solid Elastic Lens (SEL)

The SEL is a simple system composed of a mechanical mounting to which radial forces can be applied by means of a system of encrusted cogs within the transparent elastic material which makes up the body of the lens (see figure 5).

By using elastic material as surfaces of the SEL, the original shape of the lens can be deformed, and recovered when the radial forces are withdrawn. The SEL is made of aluminium and of PoliDiMethilSiloxane (PDMS) Sylgard 184 elastomer. (see figure 6). A developed study carries a description of the design, manufacture and functional characterization of the SEL [19] where the rotation of a toothed disk applies radial forces on the lens.

![Figure 5. Mechanical system for apply radial forces to the SEL.](image)

![Figure 6. Front view of the SEL with cogged disk for applying radial forces.](image)

The initial shape of the lens (without any forces) has two spherical surfaces with the same curvature radii. These surfaces will change shape as radial forces are applied on the perimeter of the lens by means of a rotating cogwheels mechanism that applies continuous linear forces.
The axial and marginal thickness and the refraction index were measured experimentally, \((t = 4.22 \, \text{mm}, \, e = 2 \, \text{mm}, \, n = 1.4157\) respectively), and from this data the curvature radii of the biconvex lens were found with an \(r = 101.90635 \, \text{mm}\) (the diameter of the lens was 30 mm). These parameters were put into the OSLO program and a ray trace was performed for the lens (see table 3 and figure 7).

| Curvature radius | Thickness | Aperture radius | Material |
|------------------|-----------|----------------|----------|
| 101.91           | 4.22      | 15             | PDMS     |
| -101.91          | 15        |                |          |

![Figure 7. Schematic diagrams of the SEL.](image)

The figures 8 and 9 show the spot diagram and wavefront aberrations found in the lens without forces applied on the border of the lens.

![Figure 8. Wavefront aberrations found in the SEL.](image)

![Figure 9. Spot diagram produce by SEL without forces applied.](image)

The values of the aberrations found in the SEL without forces applied are shown in table 4, \(\lambda = 632.8 \, \text{nm}\) was the wavelength employed to do calculations.

| Spherical | Coma | Astigmatism | Petzval | Distortion |
|-----------|------|-------------|---------|------------|
| 9.563885  | 1.1434e-06 | -6.9816e-12 | -5.3301e-12 | 3.0239e-18 |

In the next section, we describe the opto-mechanical design of the tunable lenses when the liquid medium exerts pressure on the membranes and when forces on the border of the SEL are applied.
4. Opto-mechanical Analysis

A schematic diagram of both type of tunable lenses are shown in figures 10 and 11. The mechanical mounts are manufactured of aluminum and the bodies of the lenses are made of Polidimethilsiloxane (PDMS). The tunable liquid lens is composed of a mechanical mounting, water and two PDMS membranes, the SEL is composed of a mechanical mount and a PDMS body (refractor medium). The membranes have meniscus shape with aspherical surfaces. The solid lens has spherical shape surfaces.

![Figure 10. Tunable liquid lens. (a) Isometric view, (b) mechanical components and (c) assembly of mechanical components of liquid lens.](image)

![Figure 11. SEL. (a) Assembly of mechanical components (b) mechanical components and (c) SEL assembly.](image)

The mechanical components of liquid lens are shown in the figure 10(b). Once assembly the mounting lens see figure 10(c), liquid is introduced to fill the chamber. To study the opto-mechanical performance of the proposed lenses, we use the properties of the PDMS to made simulations of the mechanical performance. The properties of the PDMS material employed in the elastic membranes and body lens are shown in the table 5.

| Parameter                             | Value                      |
|---------------------------------------|----------------------------|
| Young Modulus                         | 1.2 MPa (MN/m2)            |
| Poisson’s ratio                       | 0.46                       |
| Shear Modulus                         | 411 KPa (KN/m2)            |
| Density                               | 9.82x10^-4 gr/mm3          |
| Traction limit                        | 2.5 MPa (MN/m2)            |
| Stress limit                          | 700KPa (KN/m2)             |
| Thermal Conductivity                  | 0.2 W/(m-K)                |
| Coefficient thermal Expansion         | 310µm/(m°C)                |
| Wavelength cut                        | 240 nm                     |
| Refraction index                      | 1.427                      |
| Absorption                            | 0.04%                      |
| Transmittance in visible region       | Up 95%                     |
| Tensile limit                         | 1.9 MPa                    |
Simulations of a static analysis (MTF) of the lenses were made, to do that, we used element finite tools provided by SolidWork and ANSYS. Simulation maps of the stress, deformations and displacement of the body lenses are shown in the figures 12, 13, 14 and 15. This process is made by simulated the application of pressure and forces on the lenses.

Figure 12. Meshing of lens surfaces. (a) Meshing liquid lens, and (b) Meshing of SEL

Figure 13. Displacement map of the lens surfaces (a) when liquid pressure is applied and (b) when forces on the border are applied.

Figure 14. Deformations map of the body lens when (a) liquid pressure is applied and (b) forces on the border are applied.

Figure 15. Maps of stress distributions on the lens when (a) liquid pressure is applied and (b) forces on the border are applied.

To the liquid lens, the coordinates of some nodes on the surfaces of the membranes were measured to know the lens shape when values different of pressure were applied. To do this, We use Genetic Algorithms, the results are shown in Table 6. A transversal view of some measured points and coordinates of some nodes are shown in the figure 16. A graph of distribution of points in the plane XY is showed in the figure 17.
Table 6. Geometrical parameters obtained when pressure is applied.

| Applied Pressure | Surface 1 | Surface 2 | Thickness |
|------------------|-----------|-----------|-----------|
| 0.5 Pa           | $r = 788.32$ | $r = 408.68$ | 0.08      |
|                  | $K = -1.196$ | $K = -1.978$ |           |
| 1 Pa             | $r = 94.81$  | $r = 236.55$ | 0.07      |
|                  | $K = -1.377$ | $K = -0.988$ |           |
| 5 Pa             | $r = -67.30$ | $r = -55.573$ | 0.02     |
|                  | $K = -1.481$ | $K = -0.849$ |           |

To know the optical behavior of the proposed lens, the geometrical parameter was introduced in the OSLO™
optical design software, for this, a trace ray was made; we considered that the object is located at infinite. We show a view of the surfaces of the membrane to one applied pressure of 0.5 Pa, see figure 18.

Figure 16. Coordinates of some nodes on the surface of the lens.

Figure 17. Profile of the membrane.

Figure 18. Diagrams of the tunable liquid lens to 0.5 Pa of pressure.

Figure 19. Wavefront aberrations present in the tunable liquid lens when we applied pressure of 0.5 N/m².

Figure 20. Spot diagram produce by tunable liquid lens with a 0.5 N/m² pressure applied.
The parameters of the surfaces obtained are introduced in OSLO™ program for optical performance evaluation of the lens. The final results are presented in the figure 19 and 20. The aberrations are to the case of a liquid pressure of 0.5 Pa on the lens surface.

To the solid lens, we measure the Seidel aberrations and focal length of experimental way. The figure 21 shows the experimental interferogram of the lens to different applied stress. The figures 22 and 23 show the seidel aberrations and focal length when we applied different forces values (rotate angles of the cogwheel).

![Interferograms of SEL generate with the PDI technique when cogwheel rotates an angle of (a) 0, (b) 10.29°, (c) 20.57°, (d) 30.86°, (f) 41.14°, (g) 51.43°, (h) 56.57°, (i) 61.71° and (j) 66.86° degrees respectively.](image)

![Graph of back focal length against the angular displacement of the cogwheel.](image)

Figure 21. Interferograms of SEL generated with the PDI technique when cogwheel rotates an angle of (a) 0, (b) 10.29°, (c) 20.57°, (d) 30.86°, (f) 41.14°, (g) 51.43°, (h) 56.57°, (i) 61.71° and (j) 66.86° degrees respectively.

Figure 22. Changes in aberrations with angular rotation of the cogwheel.

Figure 23. Graph of back focal length against the angular displacement of the cogwheel.

We show the opto-mechanical design of two type of tunable lens, also we describe experimental optical behavior of the solid lens and simulations of the tunable liquid lens performance. The results show that the tunable liquid lens has better performance than the SEL. An interesting case is to SEL with conic surfaces. In the future, we will make the comparison of the lenses when both types are formed by conic surfaces.

5. Conclusions
The experimental results showed that the liquid lens had a focal range greater than the solid lens. The study and analysis of the lenses were performed with the SolidWork™ software. With SolidWork simulations for liquid lens and with a fitting program developed with genetic algorithms, we obtained the shape of the lens surfaces. The geometrical parameters of the lens were introduced in OSLO™ program for their optical performance evaluation. The design and construction of a new solid elastic lens was proposed, this lens being of the tuneable focus type. This design differs radically from those
developed so far. It requires only a mechanical mount to apply radial forces at the edge of the lens which is made from a transparent elastic material. In a future work, we make the comparison between lenses of the same type but formed with conic and spherical surfaces.

6. References

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