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Optical Model of a Human Eye's Crystalline Lens Based on a Three-layer Liquid Lens

Meimei Kong*, Xin Chen, Yang Yuan, Rui Zhao, Tao Chen, and Zhongcheng Liang

School of Electronic and Optical Engineering & School of Microelectronics,
Nanjing University of Posts and Telecommunications, Nanjing 210023, China

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Based on liquid-lens technology and our previous findings on the optical model of the Chinese eye, the liquid lens is applied in the research of the crystalline-lens optical model. Theoretical models of three-layer liquid lenses are built with COMSOL software, and the effect of voltage on the shape of the interface between two liquids is analyzed. By polynomial fitting, different equations describing the interface shape are set up under different voltages. Finally, the optical system of the human eye with a three-layer liquid lens is built and analyzed with Zemax optical design software, and moreover the optical system models of emmetropia, myopia, and hyperopia are presented. This method to build a model of the human eye with a variable-focus liquid lens can provide a novel idea for more practical human-eye models for clinical regulation and control in the future.

Keywords : Vision modeling, Ophthalmic optics and devices, Geometric optical design
OCIS codes : (330.7326) Visual optics, modeling; (220.3620) Lens system design; (220.1250) Aspherics; (110.2960) Image analysis

I. INTRODUCTION

The liquid lens is a novel optical element whose focal length can be varied by changing the surface curvature or internal refractive index of the lens, without mechanically moving it [1, 2]. According to the operating mechanisms and lens structure, liquid lenses can be classified into different types [3]. Among them, electrowetting and dielectrophoretic liquid lenses are promising because of their direct voltage actuation [4-6], and so are widely used in a large variety of applications, including mobile phones, surgical instruments, and miniature cameras [7]. These liquid lenses change focal length by varying the surface profile [8]. Liquid lenses have a simple yet elegant working principle, as do crystalline lenses in human eyes [9].

The crystalline lens is perhaps the least understood optical component in the human eye, as it is situated inside the eye, and as a result is difficult to characterize. It has unique optical properties that allow it to provide remarkable function within the healthy human eye: clear image formation on the retina, for both near and distant objects [10]. Therefore, in the field of ophthalmology research, the study of lens models is important for applications.

Based on the optical properties of the crystalline lens and liquid-lens technology, a three-layer liquid-lens model that characterizes lens zoom is proposed in this work. Combined with our previous work on modeling the Chinese human eye [11, 12], the optical system of the human eye with a three-layer liquid lens is presented.

II. THE THREE-LAYER LIQUID-LENS MODEL

Based on the crystalline lens's accommodative properties, a cylindrical model of a three-layer liquid zoom lens is used, which is shown in Fig. 1. The three-layer liquid structure is similar to a "sandwich", consisting of a conducting liquid, an insulating liquid, and a conducting liquid. The insulating liquid represents the crystalline lens, and the ocular media located in front of and behind the lens, the aqueous and vitreous media, are represented by the conducting liquid located in front of and behind the

*Corresponding author: kongmm@njupt.edu.cn, ORCID 0000-0001-9684-9364
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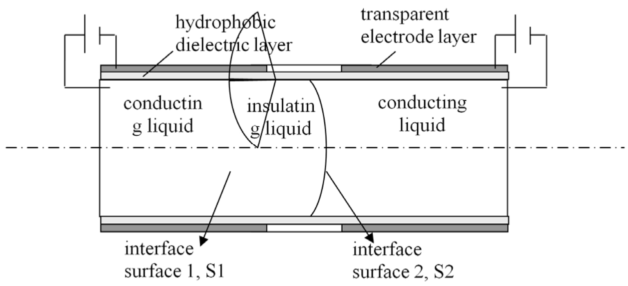
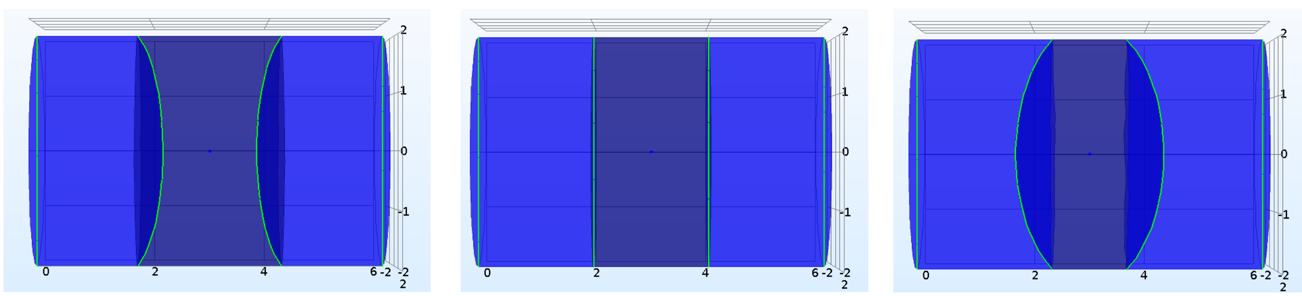


FIG. 1. Schematic cross section of the three-layer liquid-lens model for the crystalline lens's accommodation.

insulating liquid respectively.

In Fig. 1, transparent electrode layers are plated on the top and bottom of the cylindrical container, and the electrode layer is cut off in the middle of the container. Then a hydrophobic dielectric layer is deposited on the transparent electrode layer, and suitable amounts of conducting liquid, insulating liquid, and conducting liquid are injected into the container sequentially. The two liquid interfaces formed by the conducting and insulating liquids are respectively on both ends of the transparent conductive electrode. Based on the electrowetting principle, the surface profiles of the two liquid interfaces can be controlled by the applied voltages U_1 and U_2 respectively. With the different refractive indices of the insulating liquid (n_1) and conducting liquid (n_2), and the different surface types of the two liquid interfaces, this three-layer liquid lens enables the divergence or convergence of light.

According to the refractive indices of the ocular media, the mutual solubility and conductivities of the liquids, and the density difference required to ensure the asphericity of the liquid interface [13], the conducting and insulating liquids are chosen. The main component of the eye's aqueous and vitreous humors is water, so sodium chloride (NaCl) solution with a density of 1.034 g/cm^3 and a refractive index of 1.342 ($\lambda = 589.5$ nm), similar to their refractive indices, is chosen as the same conducting liquid. The insulating organic solvent dichloromethane (CH_2Cl_2), which is colorless, transparent, nonconducting, and insoluble in water, has a density of 1.3255 g/cm^3 and a refractive index of 1.4244 ($\lambda = 589.5$ nm), which is close to the average refractive index of the lens. Therefore, CH_2Cl_2 is chosen as the insulating liquid.



(a) (b) (c)

FIG. 2. Simulation diagrams of the three-layer liquid-lens model at different applied voltages: (a) $U_1 = U_2 = 30$ V, (b) $U_1 = U_2 = 80$ V, (c) $U_1 = U_2 = 110$ V.

TABLE 1. Aspheric coefficients α_i of S1 with U_1 = 80 V and different applied voltage U_2

U_2 (V)	α_1	α_2	α_3	α_4	α_5
0	-6.715×10^{-3}	2.227×10^{-3}	-3.738×10^{-4}	2.987×10^{-5}	-1.584×10^{-6}
30	-5.916×10^{-3}	1.857×10^{-3}	-2.843×10^{-4}	1.735×10^{-5}	-7.634×10^{-7}
70	-2.233×10^{-3}	5.046×10^{-3}	-9.068×10^{-5}	8.944×10^{-6}	-8.487×10^{-7}
110	-4.062×10^{-3}	2.084×10^{-3}	-4.149×10^{-4}	4.490×10^{-5}	-2.188×10^{-6}

TABLE 2. Aspheric coefficients α_i of S2 with U_1 = 80 V and different applied voltage U_2

U_2 (V)	α_1	α_2	α_3	α_4	α_5
0	6.173×10^{-2}	5.457×10^{-2}	-3.032×10^{-2}	7.633×10^{-3}	-5.890×10^{-4}
30	6.064×10^{-2}	4.091×10^{-2}	-2.269×10^{-2}	5.829×10^{-3}	-4.649×10^{-4}
70	2.273×10^{-2}	6.405×10^{-3}	-3.293×10^{-3}	8.684×10^{-4}	-7.290×10^{-5}
110	-8.931×10^{-2}	-3.314×10^{-2}	1.793×10^{-2}	-4.915×10^{-3}	4.421×10^{-4}

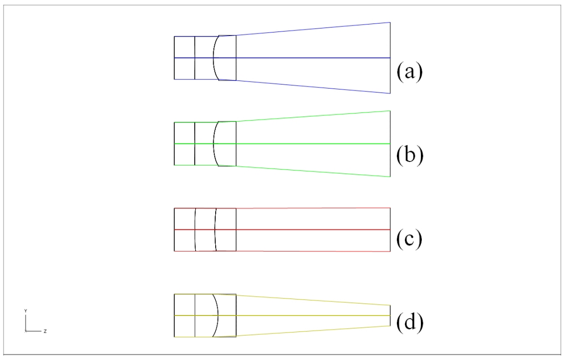


FIG. 3. Schematic plots of three-layer liquid lenses with (a) $U_1 = 80$ V & $U_2 = 0$ V, (b) $U_1 = 80$ V & $U_2 = 30$ V, (c) $U_1 = 80$ V & $U_2 = 70$ V, and (d) $U_1 = 80$ V & $U_2 = 110$ V.

By means of the COMSOL Multiphysics Software, the three-layer liquid-lens model with a pupil aperture diameter of 4 mm and a length of 6 mm is established. Figure 2 is the simulation diagram of the three-layer liquid-lens model at different applied voltages, in which the left and right parts indicate the conducting liquid and the middle part indicates the insulating liquid. From Figs. 2(a)~2(c), it is shown that with increasing voltage, the interface type gradually changes from a concave surface to a plane to a convex surface.

The aspheric interface shapes of the liquid lens are fitted with a rotationally symmetric polynomial aspheric surface (Even Asphere), which in the Zemax software is given by

$$z = \frac{cr^2}{\sqrt{(1-(1+k)c^2r^2}} + \sum_{i=1}^{8} \alpha_i r^{2i} \tag{1}$$

where c is the curvature (the reciprocal of the radius), k is the conic constant, and α_i is the aspheric coefficient, of which only the first five terms are used here.

Under different combinations of voltages U_1 and U_2, the interface surfaces S1 and S2 (shown in Fig. 1) of the liquid on either side are different. For the convenience of discussion, U_1 is set to a fixed value, such as 80 V; when U_2 takes different values, the corresponding aspheric coefficients of S1 and S2 are shown in Tables 1 and 2 respectively.

Then, the imaging characteristics of the three-layer liquid-lens model containing an aspherical surface can be obtained. Schematic plots of three-layer liquid lenses with (a) $U_1 = 80$ V & $U_2 = 0$ V, (b) $U_1 = 80$ V & $U_2 = 30$ V, (c) $U_1 = 80$ V & $U_2 = 70$ V, and (d) $U_1 = 80$ V & $U_2 = 110$ V, are shown in Fig. 3.

III. EYE MODEL WITH A THREE-LAYER LIQUID LENS

Using a similar approach, through a large number of model analyses under different combinations of voltages U_1 and U_2, the three-layer liquid-lens model suitable for representing the imaging of the lens in the human eye is finally obtained.

The human-eye model with the three-layer liquid lens under different applied-voltage combinations of U_1 and U_2 is built by using the Zemax optical design software. As shown in Fig. 4, in a Chinese generic eye model [11, 12], the variable-focus performance of the crystalline lens is simulated by replacement with a three-layer liquid lens. The pupil is not exactly centered with respect to the rest of the eye, and is often displaced slightly nasally by approximately 0.5 mm [14]. Therefore, the displacement of the third surface is introduced, as shown in Fig. 4. In Fig. 4(a), the optical element in the dashed box is the three-layer liquid lens; for the human eye model under the applied voltage combination of $U_1 = 96$ V & $U_2 = 98$ V, the incident light rays converge well at the last surface, which is represented as the retina, so this eye model can be used for the emmetropic eye. In Figs. 4(b) and 4(c), the eye models containing the three-layer liquid lens with applied-voltage combinations of $U_1 = 96$ V & $U_2 = 114$ V and $U_1 = 60$ V & $U_2 = 100$ V, which can model myopia and hyperopia respectively.

Figure 5 displays the monochromatic MTF of the eye model with the three-layer liquid lens under an applied-voltage combination of $U_1 = 96$ V and $U_2 = 98$ V, compared to the MTFs of theoretical eye models and experimental results, for a pupil diameter of 3 mm. The theoretical eye models are the Chinese generic eye model and the

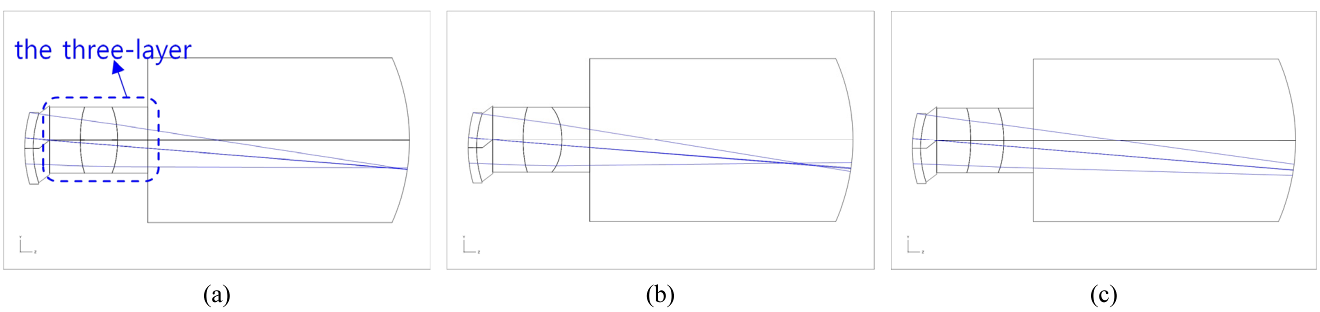


FIG. 4. Schematic plots of the eye model with a liquid lens for a pupil diameter of 3 mm, under applied-voltage combinations of (a) $U_1 = 96$ V & $U_2 = 98$ V, (b) $U_1 = 96$ V & $U_2 = 114$ V, and (c) $U_1 = 60$ V & $U_2 = 100$ V.

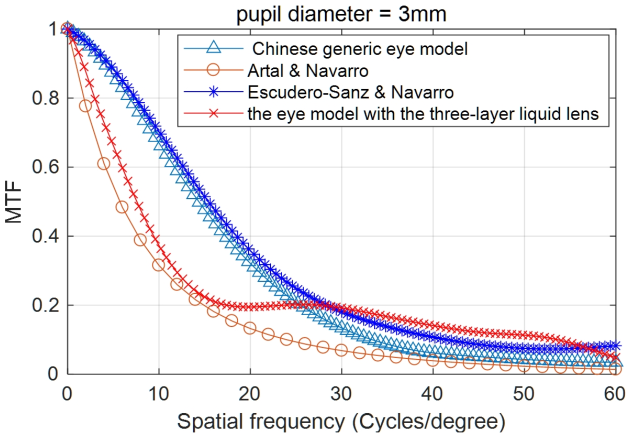


FIG. 5. The MTF of the eye model with the three-layer liquid lens (U_1 = 96 V & U_2 = 98 V), compared to theoretical eye models and experimental results.

wide-angle eye model proposed by I. Escudero-Sanz & R. Navarro [15]. The experimental results are given by P. Artal and R. Navarro [16]. In the low-spatial-frequency range, the MTF curve of the eye model with the three-layer liquid lens coincides with the experimental results roughly, and is lower than the MTFs of the two theoretical eye models. At high spatial frequencies, the MTF is roughly similar to that of the Escudero-Sanz & Navarro model, and higher than the other two data sets. Therefore, the imaging characteristics of the obtained eye model with the three-layer liquid lens, which can be used as a model of the emmetropic eye, basically conform to the imaging characteristics of the human eye.

IV. DISCUSSION AND CONCLUSION

It is feasible, then. Tto use the three-layer liquid lens as a substitute for the crystalline lens in modeling the human eye, and this method to build a human-eye model with a variable-focus liquid lens can provide a novel idea for more practical human-eye models, for clinical regulation and control in the future.

Only a representative model for myopia and hyperopia is presented in this work. In fact, the different refractive powers of myopia and hyperopia can be represented in the human eye model with a three-layer liquid lens, under the combinations of different voltages.

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