Based on MDCE to simulate bell-shaped interferograms produced by a capillary tube interferometer

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Abstract. The vector theory to calculate the optical path length (OPL) of the rays passing through a capillary tube was given and the OPLs including the collimated lens in 3D space were calculated, the interferograms produced by the capillary tube were simulated. A pinhole localized at the focal point of the collimated lens was seen as a point source of light. Based on ray-tracing, the OPL distribution from the point source of light, passing by the collimated lens, a cylindrical lens, the capillary tube and a screen was calculated. Because the huge calculation in the ray-tracing, a distributed calculating net based on MATLAB Distributed Computing Engine (MDCE) was established to save time. In order to get the simulated interferograms from the envelope of the OPLs, Delaunay triangulation algorithm and cubic spline interpolation were used. We record the interferograms of the capillary tube filled with liquids with different refractive indices and compared with the simulated interferograms. The results showed the two coincided well.

1. Introduction
Capillary tube interferometer is a new method to measure the refractive indices of transparent [1,2] or low transparent liquids[3,4]. Because fiber is a kind of solid core capillary tube, this method was also used to measure the refractive index of fiber or testing fiber [6-8]. Ramadan called this method lens–fiber interference method [8]. In above references, the experimental setup was similar, the mechanism of the interferograms was proved to be two beam interference in experiment and theoretical analysis. The simulated linear fringe patterns were the extended results in 2D space, but the experimental fringes were bell-shaped. The main reasons were the authors omitted the influence of the collimated lens and thought that the beam after the collimated lens was perfect parallel. In 2008, Yang Ailing [9] et al took account the influence of the collimated lens and simulated the interferograms in 3D space by Delaunay triangulation and sector boundary algorithm. The calculated interferograms were curved, which shows this method was effect. But Ref. 9 was lack of theoretical analysis and the calculating procedure took long time, so this problem needs a further probing.

In this paper, the vector theory to calculate the OPLs of the rays passing through the capillary tube was given and the OPLs including the collimated lens in 3D space were calculated. Because the rays will come across many interfaces with different forms, and at every interface, the refraction law [10] has to be matched. For simplicity, a 3D ray-tracing procedure on a single interface was compiled. As a ray passing through an interface, one only needs to modify the procedure slightly. Although 324×30 rays were chose to make ray tracing, the number was still limited, which caused the simulated optical
path surface was not so smooth. By using Delaunay triangulation [9,11-16], sector boundary algorithm [17-19] and cubic spline interpolation method [20-21], a smooth optical path surface was obtained. For the huge calculation, distributed computing method based on MDCE was used to make 3D ray-tracing, which saved the calculating time greatly. The simulated curved interferograms coincided well with the experiment results.

2. Experimetal setup

![Figure 1](image1.png)  ![Figure 2](image2.png)

Figure 1 shows the experimental setup. A He–Ne laser with 632.8 nm wavelength was used as a light source. After a spatial filter and a collimated lens, a parallel beam with nearly 10cm diameter was obtained. The cylindrical lens was made of K-9 glass of refractive index 1.5163, whose focal length is 31.2 cm. The inner and outer diameters of the capillary tube were 3 and 4 mm, respectively. The width of the focused beam is about 0.75mm, which is very small compared with the diameter of the capillary tube. The capillary tube is parallel to and within the focal lines of the cylindrical lens. The rays passing through the capillary tube formed an interference pattern on the screen. A high performance CCD camera recorded the interference pattern, which was stored in a computer for later digital processing.

3. Theory

When a ray passes through the elements of the capillary tube then arrives to a screen, it will intersect with spherical, cylindrical or plane interfaces. However, cylindrical and plane interfaces can be seen as special spherical interfaces, so one only needs to compile a procedure about how a ray passes through a spherical interface. For other interfaces, one only needs to modify the procedure slightly, then repeat the procedure, and can simulate the rays of the whole optical system.

Consider the refraction at a sphere interface (see figure 2). Here $O$ is the centre of the sphere interface, $R$ its radius, $n_1$ and $n_2$ are refractive indices of the surrounding medium and the lens respectively. Let $P_1P$ be the incident ray upon the sphere interface. And $PP_2$ is refracted ray. $P_2$ is the point intersection of the refracted ray and the successive surface. $\vec{N}$ is the unit normal vector of the spherical surface. $\vec{Q}_1$ and $\vec{Q}_2$ are the unit vectors of the incident and refracted rays. Assuming $P_1$ and $\vec{Q}_1$ are known, it is necessary to calculate $P$, $N$, and $\vec{Q}_2$. Assuming $R$ is finite, we could calculate $P$ and $N$ from incident light ray equation and spherical equation:

$$\begin{align*}
(\vec{P} - \vec{P}_1) &= k\vec{Q}_1, \\
|\vec{PO} - \vec{O}| &= R.
\end{align*}$$

(1)

Since there are two solutions for the spherical quadratic equation, so it is necessary to select one solution based on the selected region of the surface. If the left region of the surface is selected, $\vec{N} \cdot \vec{A} \leq 0$, otherwise $\vec{N} \cdot \vec{A} \geq 0$. Here $\vec{A}$ is the unit vector of $Y$ axis.

By the law of refraction [10],
\[ n_1 \hat{Q}_1 \times \hat{N} = n_2 \hat{Q}_2 \times \hat{N} \]
\[ |\hat{Q}_2| = 1. \tag{2} \]

\( \hat{Q}_2 \) can be obtained. For the second interface, \( PP_2 \) is incident ray. Taking into the equation of the second interface, and repeating above procedure, one can easily determine \( P_2 \) and the unit direction vector of the refracted rays. By repeated applying refraction law and the ray equation, the intersection points and the unit direction vectors can be obtained gradually.

4. MDCE

The calculating results showed that one light ray tracing on a computer (WinXP, AMD Athlon 64 Processor) cost 0.35s. 324×30 light rays will cost about 1.5h. From section 3, one can see that each light ray tracing is independent. For saving calculating time, one can take advantage of distributed computing engine to execute a lot of independent ray tracing on a group of computers. We used MDCE to realize distributed ray tracing on local area network.

![Figure 3. The distributed ray tracing diagram.](image)

Figure 3 shows the distributed ray tracing diagram. In the MDCE, two computers were used. One was assigned client (IP address: 192.168.1.200), job manager and the first worker. The other (IP address: 192.168.1.201) was as the second worker. Each worker executed tasks simultaneously. The whole ray tracing MATLAB codes were put on the client computer. The definition of ray tracing job and tasks were executed by distributed computing toolbox. When all of 324×30 rays were assigned to the two workers, each one executed 324×15 rays at the same time. The calculation results showed that the distributed ray tracing method cost about 0.8h, which saved about half time.

5. Experimental and simulated results

![Figure 4. The interferograms of ethanol (a) and (b) the collimated lens was replaced by a cylindrical lens.](image)

Figure 4 (a) shows the interferograms of ethanol when the collimated lens localized like figure 1. Figure 4 (b) is the result when the collimated lens was replaced by a cylindrical lens. One can see that the fringes are almost parallel. The reason is the two cylindrical lenses has opposite aberration, when they were put into a same optical path, their aberration will be cancelled out. Figure 4 (a) and (b) indicated that the curved fringes are relative to the collimated lens. When one calculates the OPLs, the collimated lens should not be omitted and the simulation should be in 3D space.

In the experiment, a pinhole with 15μm diameter was used as a space filter. Because it is small, we saw it as a point source of light. The OPL distribution from the point source of light, passing by the
collimated lens, the cylindrical lens, the capillary tube and the screen was calculated. Although 324×30 rays were chose to make ray tracing, the number was still limited, which caused the simulated optical path surface was not so smooth. By using Delaunay triangulation, sector boundary algorithm [17-19] and cubic spline interpolation method [20-21], a smooth optical path surface was obtained (see figure 5(b)). For the huge calculation, distributed computing method based on MDCE was used to make 3D ray-tracing, which saved the calculating time greatly. Figure 5 (a) and (c) are the experimental and simulated interferograms of auto gearing oil. The two interferograms coincides well. This oil is semi-transparent and refractive index is 1.4885. Figure 5 (d) and (e) are the experimental and simulated interferograms of ethanol, whose refractive index is 1.3510. The number of fringes of the simulated curved interferograms is less than the experimental result.

![Figure 4](image_url)

**Figure 4.** The experimental ((a) and (d)) interferograms, the simulated optical path surface (b) and the simulated interferograms ((c) and (e)). In which, (a), (b) and (c) are for auto gearing oil with 1.4785 refractive index and (d), (e) for ethanol with 1.3510.

6. Conclusion
A pinhole localized at the focal point of the collimated lens was seen as a point source of light to trace the OPLs of the rays in a capillary tube interferometer. Because the rays will come across sphere, cylindrical and plane interfaces from the pinhole to the screen. And the cylindrical and plane interfaces can be seen as special sphere interfaces. A procedure was compiled to trace a ray passing through a sphere interface. Other interfaces are only repeating of the sphere interface, which simplified the calculation. A distributed calculating net based on MDCE was established and saved about half time. Delaunay triangulation algorithm, section boundary algorithm and cubic spline interpolation were used to obtain a smooth optical path surface. Two beam interference theory was used to simulate the interferograms. The results showed the above methods were effect to simulate the curved interferograms produced by the capillary tube interferometer.

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