The Research of Optical Turbulence Model in Underwater Imaging System

Liying Sun, Junping Wang, Kecheng Yang, Min Xia, Jiefei Han

1 School of Optical and Electronic Information, Huazhong University of Science and Technology, Wuhan 430074, China
2 Hubei Polytechnic Institute, Xiaogan 432000, China
1 Tel.: 15871699399, fax: 87556617-2
E-mail: kcyang@mail.hust.edu.cn, wjp818181@163.com

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Abstract: In order to research the effect of turbulence on underwater imaging system and image restoration, the underwater turbulence model is simulated by computer fluid dynamics. This model is obtained in different underwater turbulence intensity, which contains the pressure data that influences refractive index distribution. When the pressure value is conversed to refractive index, the refractive index distribution can be received with the refraction formula. In the condition of same turbulent intensity, the distribution of refractive index presents gradient in the whole region, with disorder and mutations in the local region. With the turbulence intensity increase, the holistic variation of the refractive index in the image is larger, and the refractive index change more tempestuously in the local region. All the above are illustrated by the simulation results with the ray tracing method and turbulent refractive index model. According to different turbulence intensity analysis, it is proved that turbulence causes image distortion and increases noise. Copyright © 2014 IFSA Publishing, S. L.

Keywords: Imaging system, Underwater turbulence model, Refractive index distribution, Ray tracing, Light intensity simulation.

1. Introduction

In the marine environment, the refractive index distribution of water would be changed by the water pressure, density, temperature and salinity [1]. When the change of the distribution of refractive index of water is acute, there will be a greater impact on the optical imaging system, and it will lead to imaging distortions and image noise. In the real ocean environment, refractive index of underwater turbulent changes quickly. It is one of the important factors affecting the laser underwater imaging distance and image quality. Turbulence, which is the main cause of the changes, is widely distributed in the real ocean. Therefore, we need to take into account the influence of turbulence in the underwater imaging system. Through the research of underwater turbulence effects on the distribution of refractive index, the deformation of image and image noise affected by the turbulence under water are obtained, which also can be used for image restoration.

In recent years, with the development of computer fluid dynamics, the subject is more and more to promote the development of shallow water hydrodynamics. In this paper, with the aid of computer fluid dynamics to simulate the underwater turbulence, the turbulent models with different Reynolds number in a specific environment are obtained; the models of underwater imaging system for imaging through turbulence can be established with principles of optics.
2. Simulation of Underwater Turbulence

The density, temperature, pressure and salinity of water will have an affect on the water refractive index distribution. In the static water, the changes of water density, temperature, pressure and salinity in small area are relatively small, and will not produce upheaval. But in the dynamic water, various factors to produce a change, the change of water pressure is large especially with the fast flow speed [2-3]. When the water reaches a certain speed, it will produce turbulence. Changes of pressure and temperature distribution of water is very severe, and influence on the distribution of refractive index is also great [4]. Therefore, the water pressure and temperature distribution is the main consideration in the study of the effect of turbulence on the refractive index of water.

In this paper, the FLUENT software which is commonly used in computer fluid dynamics is first used to simulate underwater turbulence. The size of simulation model is a cuboid structure with \(0.4 \times 0.4 \times 2\) (m), in which the water inlet is a square with length of side 0.04 m, as shown in Fig. 1.

In the same turbulent size, the faster flow will make greater turbulence intensity. In this paper, the inlet flow velocity is set different with the same external dimensions of turbulence, the turbulence model under different turbulence intensity will be obtained, the simulation results under different turbulence intensity obtained are as follows in Fig. 2.

From the simulation results on the above, the faster water flows, the greater the turbulence pressure in water changes, and the lager the turbulence absolute pressure value is.

3. Turbulent Refractive Index Distribution

The research work of water refractive index began in the late eighteenth Century [5-7]. Refractive of water is first obtained by experimental data. Researchers measure refractive index of water in different temperature, pressure, salinity and wavelength. According to research by I. Thomahlen et al., the relationship formula between the refractive index and wavelength is obtained.

Compared with new measurement data values by Achtermann and Scheffler [8, 9], the using range of this equation is relatively narrow. This equation can only be used for liquid water, and the effective range of temperature is not expanded. But experiments has been satisfied by its range, and compared with former equations, the accuracy of this equations has been greatly improved.

The index of every 3D coordinate point’s rate can be calculated by refractive index function, so as to obtain the refractive index distribution. Each of the 3D coordinate points of refractive index will be calculated using the refractive index formula, and the refractive index distribution of underwater turbulence is as shown in the Fig. 3 below.
As we can see from the charts, in the conditions of the same flow speed, the distribution of refractive index presents gradient in the whole region, the refractive index near the outlet changes relatively tempestuously than the refractive index near the inlet; distribution of refractive index is disordered and mutational in local areas, the variation tendency of refractive index is unforeseen in local area, and in different local regions, the distribution of refractive index has great otherness. In the conditions of different flow velocity, the differences of the overall distribution of refractive index are great, and there is no fixed rule. It can be analyzed from the difference of refractive index that, the flow speed is faster, difference between the maximum and minimum value of the refractive index in the whole area is larger.

4. Ray Tracing

The turbulence flow is divided into many small cubes representing small turbulence element in survey region in this paper. The refractive index of each small turbulence element is different. Due to the small size of turbulence element, the small turbulence element is equivalent to small transparent sphere with the same diameter for convenient calculation. The spheres are closely packed together. The turbulence element can be considered homogeneous medium with isotropic internal refractive index [10].

Ray tracing is a display method, which is put forward by Appel in 1968. Ray tracing method based on the geometrical optics. One light is given the initial position and direction, and the light coordinates (space coordinates and the direction cosine) of adjacent points can be calculated with the ray equation. We will track down radial path into many small light steps. Combined with the method of numerical calculation, the light trajectories in changing refractive index medium will be obtained. For most of the transmission medium, satisfactory numerical solution can be obtained by ray tracing algorithm [11].

The key point of ray tracing algorithm is intersection operation of light with the object. Setting the starting point of light to O, the unit direction vector to V, parametric function of the light can be written as:

\[ R(t) = O + V \cdot t \]  \hspace{1cm} (1)

The intersections which from starting point O left along the direction of V are concerned, so the intersections with parameter \( t < 0 \) will not be considered. Set the spherical center to C and radius to r, the sphere equation is:

\[ \|X - C\| = r, \]  \hspace{1cm} (2)

where X is the points on the sphere, the ray function is substituted into the spherical equation and the tidy as:

\[ at^2 + bt + c = 0, \]  \hspace{1cm} (3)

where \( a = V \cdot V, \ b = 2V \cdot (O - C), \) and \( c = \|O - C\|^2 - r^2. \)
If discriminant is \( \Delta = b^2 - 4ac < 0 \), the quadratic equation is no solution, the light and spherical without point of intersection. If \( \Delta = 0 \), the light and spherical is tangent with only one intersection point. If \( \Delta > 0 \), the light has two intersections with spherical. Set the parameter values to \( t_1, t_2 \) respectively, which can be substituted into ray function to acquire intersection point \( P \), the unit normal vector of that point will be obtained as:

\[
N = \frac{P - C}{r}
\]

When light passes through a sphere, the light change direction in the intersecting sphere to form refracted light, the relationship of Angle \( \theta_1 \) of incidence and refraction Angle \( \theta_2 \) as follows:

\[
\frac{\sin \theta_1}{\sin \theta_2} = \frac{n_2}{n_1},
\]

where \( n_1, n_2 \) respectively is the refraction index of incident light and refractive light in the space medium, \( \vec{T} \) is the unit refracted ray direction vector, \( \vec{L} \) is the unit incident ray direction vector, and \( \vec{N} \) is the unit normal vector, which three vectors are coplanar, and there are:

\[
\vec{T} = -\frac{1}{\eta} \vec{L} \left( \cos \theta_2 - \frac{1}{\eta} \cos \theta_1 \right) \vec{N},
\]

\[
\cos \theta_2 = \left( 1 - \frac{1}{\eta} (1 - \cos^2 \theta_1) \right)^{\frac{1}{2}},
\]

where \( \eta = n_2 / n_1 \) is the relative refractive index of the adjacent medium.

Ray function is the basic equation described light trajectory in changing refractive index medium. The description following:

\[
\frac{d}{ds} \left( \frac{dr}{ds} \right) = \nabla n,
\]

where \( s \) is the arc length of light path, \( r \) is the light radius vector, \( n \) is the refractive index, and \( \nabla n \) is the refractive index gradient.

In most cases equation (8) is difficult to obtained analytical solution, for light propagation path in arbitrary non-uniform refractive index medium, the general numerical solution is obtained with the method of ray tracing in a general way [12].

5. Influence on Turbulent to Light Intensity

In the turbulence area, 532 nm laser is used to the simulation by the ray tracing method, laser image and intensity distribution through the turbulence zone is obtained as shown in Fig. 4 - Fig. 6.

It can be seen that laser intensity changes after through variable refractive index medium area from the figure, and light intensity distribution also is changed. This is due to different light ray through different paths in variable refractive index medium, one part of the light deviated from the original direction refracts at a certain angle to other receiver. On the other hand, optical path of light deviating different direction also produces changes, causing the different light attenuation, deformation of light distribution is produced on the receiving surface.
6. Conclusions

By using computational fluid dynamics and the formula of refractive index, this paper finally got the turbulence refractive index three-dimensional distribution data. In the condition of same turbulent intensity, the distribution of refractive index presents gradient in the whole region, with disorder and mutations in the local region. In the conditions of different flow velocity, the differences of the overall distribution of refractive index are great, and there is no fixed rule. Faster the water flow is, larger the difference between the minimum and maximum values of the refractive index is. The water velocity is faster, the holistic variation of the refractive index in the image is larger, and the refractive index change more tempestuously in the local region. The laser intensity distribution has changed through the turbulent area reduction; it will cause image distortion and noise. The effect on the imaging of turbulence in the low velocity is not large, and there will be a weak change of the effect of light and shade on the image.

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References


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