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Study on Light Scattering Characteristics of Single Bubble

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Abstract: The Mie scattering theory of a single bubble is used to solve the problems of different bubble radius scattering intensity distribution and scattering phase function distribution of bubbles at different refractive index of seawater in the paper.This paper systematically describes the single bubble Mie scattering theory, which provides experimental verification and data support for the single bubble Mie scattering theory, and also has important research significance for underwater laser communication and laser guidance of submarine wake.

Keywords: He-Ne Laser; Wake Bubble; Mie Scattering; Scattering Phase Function; Polarized Light

1. Introduction

In foreign countries, the earliest research on the optical properties of wakes was in 1955.Based on the study of single bubble scattering theory, Davis concluded the scattering characteristics of larger bubbles. Marston et al. [2] further studied the light scattering characteristics of bubbles. M.K. Akbar, S.M. Ghiaasiaan et al [3] simulated the scattering problem of rising bubbles suspended in a pool based on the mixed Euler-Monte Carlo method. The research on the optical properties of wake bubbles started relatively late in China, Zhang Jiansheng [4] first proposed a mathematical model of wake characteristics to describe the acoustic, optical, and thermal properties of the wake in detail, filling the gap in the research on the optical properties of the wake in China. Later, In 2006, Cao Jing [5] used the Monte Carlo method to simulate and calculate the light scattering characteristics of bubbles in water based on Mie scattering theory. Yang Yu [6] calculated the stokes vector of the forward scattering light of the bubble screen through the Monte Carlo simulation of the polarization light transmission characteristics, and studied the polarization characteristics of the forward scattering light of the bubble screen when the linearly polarized light and the circularly polarized light are incident. In 2013, Sun Jianpeng [7] calculated the optical scattering efficiency, scattering phase function, and intensity distribution of a single bubble based on Mie scattering theory. Chen Yan [8] measured the forward scattering illuminance of laser and studied the effects of different pressures and media on the forward scattering light of laser.

2. Mie Scattering Theory of Single Bubble

When a non- polarized monochromatic light with a wavelength of λ irradiates a bubble, with scattering angle θ, and distance between observation point to finite bubble r, the scattering intensity is

$$I_s = I_0 \frac{\lambda^2}{8\pi^2 r^2}\left[\left|S_1(\theta)\right|^2 \sin^2\varphi + \left|S_2(\theta)\right|^2 \cos^2\varphi\right] \tag{1}$$

S_1, S_2 are amplitude function.

$$S_1(\theta)=\sum_{n=1}^{\infty}\frac{2n+1}{n(n+1)}\left[a_n\pi_n(\cos\theta)+b_n\tau_n(\cos\theta)\right]$$
$$S_2(\theta)=\sum_{n=1}^{\infty}\frac{2n+1}{n(n+1)}\left[a_n\tau_n(\cos\theta)+b_n\pi_n(\cos\theta)\right] \quad (2)$$

a_n , b_n are the Mie scattering coefficient.

$$a_n=\frac{m\varphi_n(m\alpha)\varphi_n'(\alpha)-\varphi_n(\alpha)\varphi_n'(m\alpha)}{m\varphi_n(m\alpha)\xi_n'(\alpha)-\xi_n(\alpha)\varphi_n'(m\alpha)}$$
$$b_n=\frac{\varphi_n(m\alpha)\varphi_n'(\alpha)-m\varphi_n(\alpha)\varphi_n'(m\alpha)}{\varphi_n(m\alpha)\xi_n'(\alpha)-m\xi_n(\alpha)\varphi_n'(m\alpha)} \quad (3)$$

φ_n, ξ_n are Bessel function and Hankel function.

When non polarized light is incident, the intensity of the scattered at a position with a scattering angle θ of is

$$I_s(\theta)=\frac{\lambda^2}{8\pi^2R^2}I_0\left[i_1+i_2\right] \quad (4)$$

When the incident light is polarized, the intensity of the scattered at the position where the scattering angle θ is

$$I_s(\theta)=\frac{\lambda^2}{8\pi^2R^2}I_0\left[i_1\sin^2\phi+i_2\cos^2\phi\right] \quad (5)$$

ϕ is the angle between the incident photoelectric vector and the scatteringplane. The scattered light of a wake bubble is partially polarized, and the parallel and vertical components can be expressed as

$$I_P(\theta)=\frac{\lambda^2}{4\pi^2R^2}I_0i_2 \qquad I_V(\theta)=\frac{\lambda^2}{4\pi^2R^2}I_0i_1 \quad (6)$$

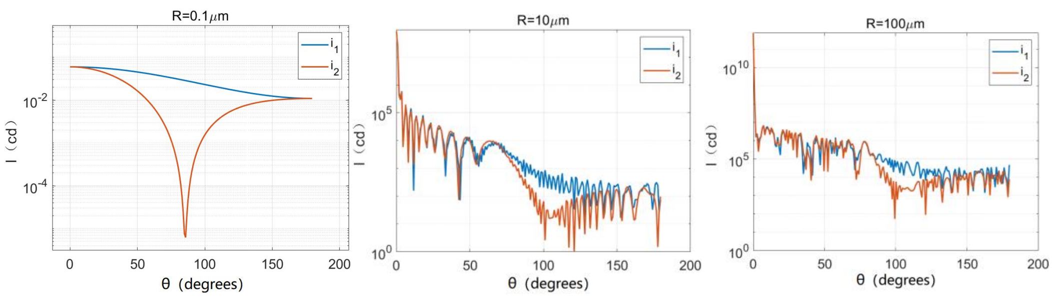
The expression for the degree of polarization is

$$DOP=\frac{I_V-I_P}{I_V+I_P} \quad (8)$$

3. Simulation analysis

3.1 The simulation results of different bubble radii

Figure 1 (a-d) calculates the scattering of a single bubble when the wavelength is 632.8 nm , the relative refractive index n is 0.75, and the bubble radius a is 0.1, 1, 10, and 100 μm , respectively.



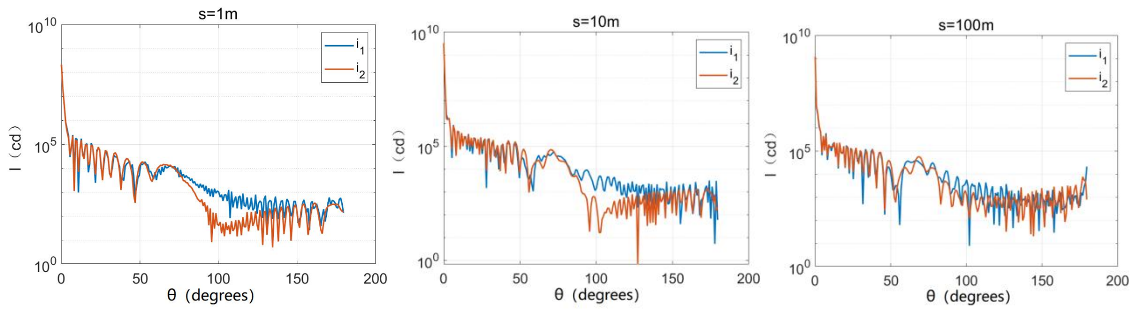
(a)R=0.1 μm (b) R=10 μm (c) R=100 μm

Fig. 1 Scattered light intensity distribution with different bubble radius

The simulation results for bubble scattering with different radii show that the main intensity of scattered light is concentrated at 0 degrees. When the bubble radius is very small, the intensity difference between forward and backward scattered light is not significant, and the scattered light varies uniformly in all directions.When the bubble radius increases to 1 μm , the back scattering light is significantly smaller than the forward scattered light, and the scattered light intensity begins to fluctuate in spatial distribution.When the bubble radius increases to 100 μm , the back scattering intensity continues to increase.

3.2 Simulation results for different detection distances

Set the bubble radius to 20 μm ,Figure 2 (a-c) calculates the scattering of a single bubble at a wavelength of 632.8 nm , the distance from the light source to the bubble of 1, 10, 100 m , respectively. The difference in the distance between the light source and the bubble determines the size of the scattering intensity. As the distance between the light source and the bubble increases, the scattering intensity gradually decreases. The intensity of forward scattering is significantly greater than that of back scattering.



(a) S=1 m (b) S=10 m (c) S=100 m

Fig. 2 Intensity distribution of light scattered by bubbles at different distances from light source to bubble

3.3 Detection results of different relative refractive indices

Figure 5 shows the distribution of phase functions at different relative refractive indices.

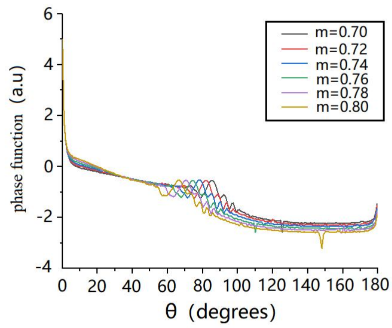


Fig. 5 Distribution of bubble scattering phase function at different sea water densities

Overall, the trend of phase functions is similar. At 0 degrees and 180 degrees, the scattering phase functions remain consistent, indicating that the values of the scattering phase functions for forward and backward scattering of bubbles remain unchanged regardless of the relative refractive index environment. There are slight differences in the size of the scattering phase functions between 0 degrees and 30 degrees, and their size decreases as the relative refractive index increases. In the range of 45 degrees to 100 degrees, the value of the scattering phase function does not change much, but there are significant differences in the angular distribution. The larger the relative refractive index, the higher the distribution position of the scattering phase function. In the range of 100 degrees to 179 degrees, the size of the scattering phase function changes, as the greater the relative refractive index, the lower the value of the scattering phase function.

4. Conclusion

In this paper, the Mie scattering theory of a single bubble is solved to simulate the scattered light intensity distribution of wake bubbles in different environments. The conclusions are as follows:Overall scattering intensity, and backscattering attenuate monotonically with the distance between light source and the bubble. The farther the light source is from the bubble, the weaker the backscattering is.The greater the density of seawater, the greater the volatility of the scattering intensity distribution, and the more complex the scattering situation. When the scattering angle is between 50 degrees and 80 degrees, the change in the scattering intensity is not significant compared to other angles.

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