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Scattering of aggregated particles illuminated by a zeroth-order Bessel beam

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ABSTRACT

In this paper, the scattering of aggregated particles illuminated by a zeroth-order Bessel beam is investigated using the generalized Lorenz-Mie theory (GLMT). The beam shape coefficients (BSCs) of the zeroth-order Bessel beam are computed rigorously using analytical expressions. Numerical results concerning the scattering properties of aggregated particles located on the propagation axis of the incident zeroth-order Bessel beam are presented. The influences of the half-cone angle of the Bessel beam, the radius and the refractive index of the particles on the scattering pattern are discussed.

1. Introduction

Recent years, Bessel beams are widely used in various fields such as optical manipulation, and imaging [1–4]. Although ideal Bessel beams can hardly be realized, high-quality quasi-Bessel beams can be obtained in practical experiments by different approaches [5,6]. Among the studies of the Bessel beams, the scattering of Bessel beam by small particles is a basic and important topic, which attracts a lot of attention in recent years. Scattering of a zeroth-order Bessel beam by a homogeneous spherical particle was described by Marston et al. [7], where the Bessel beam was expanded in terms of partial waves. A similar method was applied by Mitri [8] on the analysis of scattering of high-order Bessel beam by a homogeneous sphere. The scattering of an unpolarized Bessel beam by a spherical particle was studied by Ma and Li [9], where the Bessel beam was expanded in terms of vector spherical wave functions (VSWFs). Light scattering of an on-axis zeroth-order Bessel beam by a concentric sphere was analyzed by Chen et al. [10] in the framework of generalized Lorenz-Mie theory (GLMT), where the beam shape coefficients (BSCs) were evaluated using the localized approximation (LA) method. Later this method was also extended to the investigation of a multilayered sphere [11]. The GLMT is a rigorous method based on the separation of variables, it provides a powerful tool to deal with the interaction between arbitrary shaped beams and regular shaped particles, such as spheroidal particles [12], particles with eccentric inclusion [13], aggregated particles [14], and so on. The aggregated particles illuminated by a plane wave has been analyzed by Xu [15]. This method was extended recently to the case of aggregated particles illuminated by an arbitrary shaped beam by Briard et al. [16], where results were presented for a focused Gaussian beam illumination.

In this paper, the case of aggregated particles (spherical, homogeneous, isotropic) illuminated by a zeroth-order Bessel beam, in the on-axis case, is studied using the GLMT. The left part of the paper is organized as follows. Theoretical treatments are briefly revisited and presented in Section 2. Numerical results concerning the angular distributions of scattered intensity are presented in Section 3. Section 4 is a conclusion.

2. Theoretical treatments

A theoretical treatment of light scattering by aggregated particles illuminated by an arbitrary shaped beam was originally presented by Gouesbet and Grehan [14] within the framework of GLMT, although no numerical results were given. In this section, the theoretical treatment is briefly revisited and presented for the light scattering by aggregated particles with an illumination of a zeroth-order Bessel beam.

To describe the 3D locations of the primary particles in an aggregate, a Cartesian coordinate system ($Oxyz$) is used, where the origin O of the Cartesian coordinate system is assumed to lie in the center of. The propagation direction of the incident zeroth-order Bessel beam is assumed along the z-axis. To describe the electromagnetic scattered and incident fields, a spherical coordinate system (ρ,θ,ϕ) is also assumed to attach to the j th primary particle. The $\rho=kr$ is the non-dimensional radial coordinate (where k is the wave number and r is the radial coordinate), θ is the polar angle, and ϕ is the azimuthal angle. These two coordinate systems are illustrated in Fig. 1.

Furthermore, in the special case of Bessel beam illumination, the geometry of an aggregated particle illuminated by an incident zeroth-

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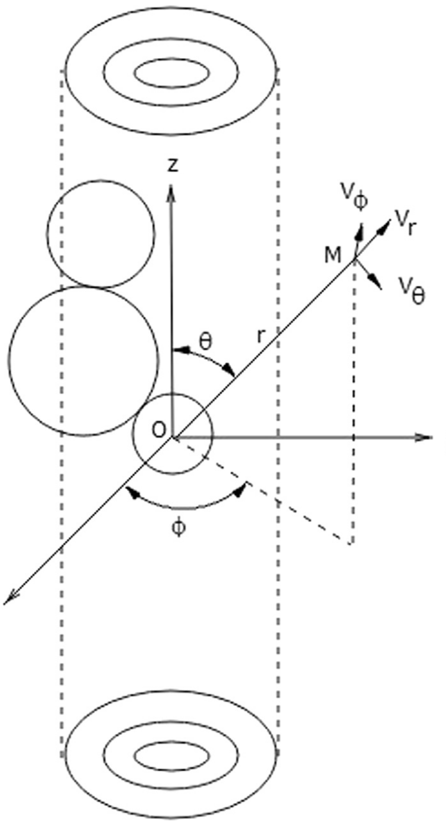

Fig. 1. Scheme of an aggregated particle illuminated by an arbitrary shaped beam. Two sets of coordinate systems are used: the Cartesian coordinate system ($Oxyz$) used to describe the 3D locations of the primary particles and the spherical coordinate system (ρ=kr,θ,ϕ) used to describe the incident and the scattered fields.

order Bessel beam is displayed in Fig. 2.

As shown in Fig. 2, the incident Bessel beam is attached to a Cartesian coordinate system $O_b uvw$, where O_b is located at the center of the beam. The Bessel beam propagates along the w-axis. The axes $O_b u$, $O_b v$ and $O_b w$ are parallel to the axes Ox, Oy and Oz, respectively. The coordinates of O_b in the Cartesian coordinate system $Oxyz$ is denoted as $\{0, 0, z_0\}$. Explicit expressions for the field components of a zeroth-order Bessel beam was given by Mishra [17] as

$$E_u = \frac{1}{2}E_0\left[\left(1 + \frac{k_w}{k} - \frac{k_r^2 u^2}{k^2 r^2}\right)J_0(k_r r) + \frac{k_r(v^2 - u^2)}{k^2 r^3}J_1(k_r r)\right]e^{ik_w w}, \tag{1}$$

$$E_v = \frac{1}{2}E_0 uv\left[\frac{2k_r}{k^2 r^3}J_1(k_r r) - \frac{k_r^2}{k^2 r^2}J_0(k_r r)\right]e^{ik_w w}, \tag{2}$$

$$E_w = \frac{1}{2i}E_0\frac{u}{kr}\left(1 + \frac{k_w}{k}\right)k_r J_1(k_r r)e^{ik_w w}, \tag{3}$$

$$H_u = \frac{\sqrt{\varepsilon}}{2}E_0 uv\left[\frac{2k_r}{k^2 r^3}J_1(k_r r) - \frac{k_r^2}{k^2 r^2}J_0(k_r r)\right]e^{ik_w w}, \tag{4}$$

$$H_v = \frac{\sqrt{\varepsilon}}{2}E_0\left[\left(1 + \frac{k_w}{k} - \frac{k_r^2 v^2}{k^2 r^2}\right)J_0(k_r r) + \frac{k_r(u^2 - v^2)}{k^2 r^3}J_1(k_r r)\right]e^{ik_w w}, \tag{5}$$

$$E_w = \frac{\sqrt{\varepsilon}}{2i}E_0\frac{v}{kr}\left(1 + \frac{k_w}{k}\right)k_r J_1(k_r r)e^{ik_w w}, \tag{6}$$

where $\{E_u, E_v, E_w\}$ and $\{H_u, H_v, H_w\}$ are the components of the electric and magnetic incident field in the system $O_b uvw$. $k_r = k\sin\alpha$ and $k_w = k\cos\alpha$ are the transverse component and the longitudinal component of the wave number $k = 2\pi/\lambda$. α is the half-cone angle of the zeroth-order Bessel beam. J_0 and J_1 are the cylindrical Bessel function of the zeroth-order and the first-order, respectively. $r = \sqrt{u^2 + v^2}$ is the radial distance to the w-axis.

On one hand, in the spherical coordinate $(\rho^j, \theta^j, \phi^j)$, whose origin is centered on the jth particle, an arbitrary shaped beam can be expanded in terms of VSWFs as [15]

$$\mathbf{E}_{inc}^j(\rho^j, \theta^j, \phi^j) = -\sum_{n=1}^{\infty}\sum_{m=-n}^{n} iE_{mn}[p_{mn}^j \mathbf{N}_{mn}^{(1)}(\rho^j, \theta^j, \phi^j) + q_{mn}^j \mathbf{M}_{mn}^{(1)}(\rho^j, \theta^j, \phi^j)], \tag{7}$$

where

$$E_{mn} = E_0 i^n\left[\frac{(2n+1)(n-m)!}{n(n+1)(n+m)!}\right]^{1/2}, \tag{8}$$

the $\mathbf{M}_{mn}^{(1)}(\rho^j, \theta^j, \phi^j)$ and $\mathbf{N}_{mn}^{(1)}(\rho^j, \theta^j, \phi^j)$ are the VSWFs of the first kind, whose explicit expressions are the same as those given in [15]. p_{mn}^j and q_{mn}^j are the expansion coefficients of the incident wave, related to the jth particle.

On the other hand, within the GLMTs, the radial components of an incident electric field and magnetic field of an arbitrary shaped beam can be expressed in terms of BSCs as [18]

$$E_r = E_0\sum_{n=1}^{\infty}\sum_{m=-n}^{n}\left[c_n^{pw} g_{n,TM}^m \frac{n(n+1)}{r} j_n(kr)P_n^{|m|}(\cos\theta)\exp(im\phi)\right], \tag{9}$$

$$H_r = H_0\sum_{n=1}^{\infty}\sum_{m=-n}^{n}\left[c_n^{pw} g_{n,TE}^m \frac{n(n+1)}{r} j_n(kr)P_n^{|m|}(\cos\theta)\exp(im\phi)\right], \tag{10}$$

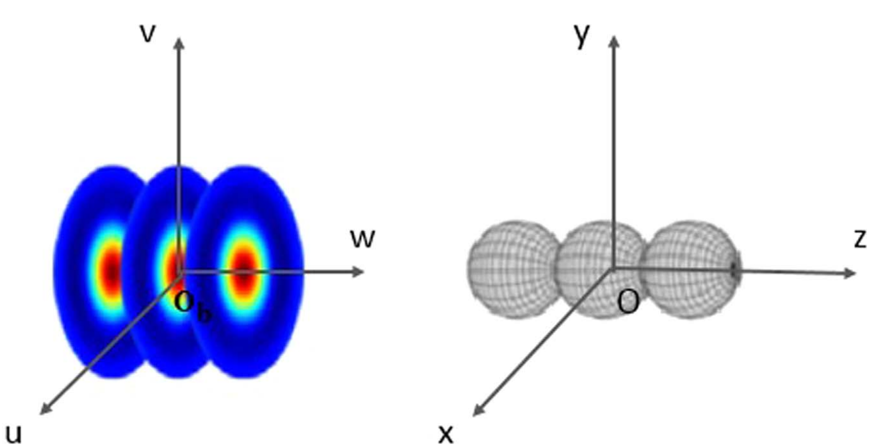

Fig. 2. Geometry of a zeroth-order Bessel beam incidents on an aggregated particle consists of three primary particles. All the primary particles are located on the propagation axis of the beam.