Journal of Quantitative Spectroscopy & Radiative Transfer 144 (2014) 108–116

Contents lists available at ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

journal homepage: www.elsevier.com/locate/jqsrt

Scattering of Bessel beam by arbitrarily shaped composite particles with core–shell structure

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A R T I C L E I N F O

Article history:
Received 25 February 2014
Received in revised form
11 April 2014
Accepted 12 April 2014
Available online 19 April 2014

Keywords:
Scattering
Bessel beam
Composite particles
Surface integral equation

A B S T R A C T

This study investigates the scattering of Bessel beam by composite particles with core–shell structure. Specifically, the vector expressions of zero-th order Bessel beam that satisfy well Maxwell's equations in combination with the rotation Euler angles are used to represent the arbitrarily incident Bessel beams. An efficient numerical method based on surface integral equations is introduced to formulate the scattering problems involving arbitrarily shaped composite particles with core–shell structure. Solutions are performed iteratively by using the multilevel fast multipole algorithm. The numerical results for differential scattering cross sections of several selected composite particles are presented and analyzed. This investigation is expected to provide useful guidance for techniques of laser detection on particle, diagnosis, and manipulation.

1. Introduction

Many particles encountered in nature or produced in industrial processes, such as raindrops, ice crystals, biological cells, dust grains, daily cosmetics, and aerosols in the atmosphere, are often found to be inhomogeneous and can be regarded as composite particles with core–shell structure. The study of light scattering by these composite particles is essential in a wide range of scientific fields and it has myriad practical applications, including optical manipulation, particle detection and discrimination, design of new optics devices, etc.

Over the past few decades, the scattering of plane wave by various composite particles with core–shell structure has been investigated extensively by many researchers. In recent years, with the development of laser sources and the tremendous expansion of their applications, there has been a growing interest in the study of light scattering by various core–shell composite particles illuminated by laser beams. For the case of an incident focused Gaussian beam, an early study was carried out by Khaled et al. [1]. In that paper, they applied the T-matrix method to examine the scattering of an off-axis Gaussian beam by a concentrically layered sphere. Later, within the framework of the generalized Lorenz–Mie theory (GLMT) [2], Gouesbet and Gréhan [3], Han et al. [4], Yan et al. [5], and Wang et al. [6,7] investigated the scattering of an arbitrarily incident Gaussian beam by an eccentrically layered sphere. Subsequently, Zhang and Liao [8] adopted the GLMT to study the Gaussian beam scattering by a spherical particle with a spheroidal inclusion. Yan et al. [9] investigated the case of a spheroidal particle with a spherical inclusion. In addition, Sun et al. [10] constructed an analytic solution to the Gaussian beam scattering by a conducting spheroid with a confocal dielectric coating. Despite some studies, as reviewed herein, have been carried out on the scattering of Gaussian beam by several kinds of composite particles with core–shell structure, these studies mainly focused on the cases of regular composite particles. Recently, we introduced an efficient numerical method based on surface integral equations to characterize the scattering of an arbitrarily

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http://dx.doi.org/10.1016/j.jqsrt.2014.04.007

incident focused Gaussian beam by arbitrarily shaped composite particles with internal inclusions [11]. Nevertheless, to the best of our knowledge, the scattering of Bessel beam by composite particles with core–shell structure has not been reported. In fact, the Bessel beam, as another kind of laser beam, has attracted widespread attention in various fields ever since its first introduction by Durnin [12,13], because of its special characteristics of non-diffraction and self-reconstruction. The purpose of this paper is to study the scattering of Bessel beam by composite particles with core–shell structure and arbitrary shapes. In view of the zero-th order Bessel beam has the typical characteristics of non-diffraction and self-reconstruction, and can be easily realized in the laboratory; here we only consider the problem of scattering by core–shell structure composite particles illuminated by an arbitrarily incident zero-th order Bessel beam. Specifically, the incident beam is described by adopting the vector expressions of the zero-th order Bessel beam [14,15] in combination with the rotation Euler angles [16]. The scattering problems involving core–shell structure composite particles are formulated by utilizing the surface integral equations (SIEs) [17–19]. For numerical purposes, the surfaces of the shell and core are modeled by using small triangular patches and the SIEs are discretized with the well-known method of moments (MOM) [20]. To reduce computational burdens, the resultant matrix equation is solved by an iterative solver, where the multilevel fast multipole algorithm (MLFMA) [21–25] is used to speed up the matrix–vector multiplication.

This paper is organized as follows. In Section 2, the mathematical expressions of an arbitrarily incident zero-th order Bessel beam in terms of the electric and magnetic fields are given. Section 3 presents the formulation of the surface integral equation method (SIEM) for characterizing the scattering problems involving arbitrarily shaped composite particles with core–shell structure. Section 4 shows the numerical results of this work. Finally, Section 5 concludes the paper.

2. Description of the Bessel beam

In optics, a Bessel beam is a field of electromagnetic whose amplitude is described by a Bessel function of the first kind. Two special characteristics of a Bessel beam are its non-diffraction and self-reconstruction. It can maintain the same intensity profile and the intensively localized intensity distribution in the plane transverse to the axis of the beam, and is able to wholly reform at some distance beyond the obstruction as long as the whole beam is not blocked if it encounters an obstruction. For the fundamental zero-th order Bessel beam considered herein, it consists of a series of concentric rings with an amplitude maximum at the origin, as illustrated in Fig. 1. The mathematical function which describes a zero-th order Bessel beam is a solution of the scalar wave equation in the cylindrical coordinate system. The general representation of a zero-th order Bessel beam propagating in the $+w$ direction is given by [12]

$$A = A_0 J_0(k_r r)\exp(-ik_w w), \quad (1)$$

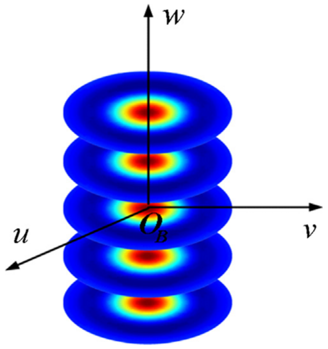

Fig. 1. Illustration of a zero-th order Bessel beam in its own coordinate system.

where A_0 is the characteristic amplitude, $J_0(\cdot)$ is the cylindrical Bessel function of the first kind of the zero-th order, the parameters $k_r = k\sin\phi$ and $k_w = k\cos\phi$ are the transversal and longitudinal components of the wavenumber k respectively, where ϕ is the half-cone angle of the incident Bessel beam in background medium. The scalar expression of the zero-th order Bessel beam described by (1) can provide satisfactory results if the size of the central spot of the beam is much larger than the wavelength, i.e., $k_r \ll k$. However, when $k_r \approx k$, the scalar expression proves to be inaccurate to describe such a Bessel beam, and must then be extended to account for the vector nature of electromagnetic waves. In 1991, Mishra [14] first recognized this type of correction and derived the vector components for the electric and magnetic fields of a zero-th order Bessel beam stemming from Maxwell's vector equations and the Lorenz gauge condition. For a zero-th order Bessel beam in the homogeneous medium propagating along the axis w in its own Cartesian coordinate system $O_B uvw$, from the negative w to the positive w, with the leading electric field polarized in the positive u-direction, the electromagnetic field components read as [14]

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

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

$$E_w = \frac{1}{2}E_0\left[i\frac{u}{kr}\left(1+\frac{k_w}{k}\right)k_r J_1(k_r r)\right]\exp(-ik_w w), \quad (4)$$

$$H_u = \frac{1}{2}H_0\left[\frac{2k_r uv}{k^2 r^3}J_1(k_r r)-\frac{k_r^2 uv}{k^2 r^2}J_0(k_r r)\right]\exp(-ik_w w), \quad (5)$$

$$H_v = \frac{1}{2}H_0\left[\left(1+\frac{k_w}{k}-\frac{k_r^2 v^2}{k^2 r^2}\right)J_0(k_r r) - \frac{k_r(u^2-v^2)}{k^2 r^3}J_1(k_r r)\right]\exp(-ik_w w), \quad (6)$$

$$H_w = \frac{1}{2}H_0\left[i\frac{v}{kr}\left(1+\frac{k_w}{k}\right)k_r J_1(k_r r)\right]\exp(-ik_w w), \quad (7)$$