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Arbitrary scattering of an acoustical Bessel beam by a rigid spheroid with large aspect-ratio

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ABSTRACT

In this paper, the *T*-matrix (null-field) method is applied to investigate the acoustic scattering by a large-aspect-ratio rigid spheroid immersed in a non-viscous fluid under the illumination of an unbounded zeroth-order Bessel beam with arbitrary orientation. Based on the proposed method, a MATLAB software package is constructed accordingly, and then verified and validated to compute the acoustic scattering by a rigid oblate or prolate spheroid in the Bessel beam. Several numerical examples are carried out to investigate the novel phenomenon of acoustic scattering by spheroids in Bessel beams with arbitrary incidence, with particular emphasis on the aspect ratio (i.e. the ratio of the polar radius over the equatorial radius of the spheroid), the half-cone angle of Bessel beam, the dimensionless frequency, as well as the angle of incidence. The quasi-periodic oscillations are observed in the plots of the far-field backscattering form function modulus versus the dimensionless frequency, owing to the interference between the specular reflection and the Franz wave circumnavigating the spheroid in the surrounding fluid. Furthermore, the 3D far-field scattering directivity patterns at end-on incidence and 2D polar plots at arbitrary angles of incidence are exhibited, which could provide new insights into the physical mechanisms of Bessel beam scattering by flat or elongated spheroid. This research work may provide an impetus for the application of acoustic Bessel beam in engineering practices.

1. Introduction

During the past few decades, investigations dealing with Bessel beams have attracted more and more attention in the fields of optics [1–5], electromagnetics [6–8] and acoustics [9–12] ever since they were introduced through theoretical and experimental investigations [13,14] . Hsu successfully produced a Bessel beam transducer by polarizing a piezoelectric ceramic disk nonuniformly [15], which provides great impetus for researchers to further explore its novel beam-forming and wave propagation properties. As is known to all, Bessel beams have been demonstrated to have several advantages over infinite plane waves and Gaussian beams, because they can propagate without distortion over a characteristic distance in free space. In addition, a Bessel beam is characterized by two important features, namely, the nondiffraction property and

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self-construction ability. The former feature means that the transverse intensity profile in the plane perpendicular to the direction of Bessel beam axis remains unaltered [14,16–18], while the second one describes the ability of the Bessel beam to reconstruct its initial intensity profile after encountering an obstacle in the case where the incident waves (forming the beam) are not blocked completely [19–21]. Owing to the superior characteristics mentioned above, acoustical Bessel beams have continued to receive increasing interest and many researchers have been devoting their efforts to study physical phenomena involving Bessel beams both theoretically and experimentally.

Recently, many studies have been carried out on the acoustic scattering of a Bessel beam interacting with rigid, soft and elastic targets. Axial radiation force of a Bessel beam on a sphere (including rigid, fluid and elastic solids spheres) was initially studied by Marston and negative (pulling) axial forces were found under certain conditions which may provide an impetus to design acoustic tweezers [9] and tractor beams [22]. After that, Marston further investigated the monostatic and bistatic (i.e. polar) scattering characteristics of both rigid and soft spheres centered on a zeroth-order [23] or high-order [22] Bessel beam. Later, the resonance scattering of an elastic solid sphere and spherical shell under the Bessel beam illumination, and influences of several selective half-cone angles on the suppression of backscattering resonance were reported in detail [24]. Subsequently, researches involving the acoustic scattering of Bessel beams were further developed by others, such as Mitri and Li's group. There has been considerable interest in Mitri's study of high-order Bessel beams to explore acoustic scattering characteristics by several objects, including rigid (movable and immovable) spheres [25–27], elastic spheres [10,28], elastic spherical shells [29,30] and rigid spheroids [31,32]. In addition, Mitri devoted much effort to further investigate the acoustic radiation force exerted by Bessel beams on spheres [33–36], and rigid spheroids [37,38] based on Zhang's general approach [39]. Similarly, our research group has studied the scattering problems of arbitrary-shape rigid scatterers facing the incident Bessel beam [40]. In our work, the backscattering fields of rigid spheroid and finite cylinder with two hemispherical endcaps were investigated, and the peak-to-peak intervals in backscattering form functions were analyzed with both geometric and numerical method.

However, as reviewed above, most of the computations associated with Bessel beam scattering have concentrated on objects with spherical geometry. Only few works [31,32,37,38] were aimed to explore the new physical phenomena of acoustical scattering of Bessel beam from nonspherical rigid obstacles by using the partial-wave series expansion (PWSE) method in spherical coordinates. However, the PWSE method suffers an ill-conditioning during matrix inversion procedures so it has the restrictions that the aspect ratio of rigid spheroid is generally smaller than 3:1. To the authors' knowledge, it still remains unpublished to calculate the acoustic scattering of a Bessel beam by a spheroid with a large aspect-ratio reaching 10:1, both in normal and oblique incidence cases. It is of some importance to study the highly elongated or extremely flat rigid spheroids which can be found in many theoretical models in fluid dynamics and engineering applications. For instance, in resonance scattering theory (RST), the scattering fields by rigid targets are always taken as non-resonant backgrounds for elastic solid and thick shell structures [41]. On this basis, it is possible to isolate the "pure" elastic resonance scattering from the total scattering fields by subtracting a corresponding rigid background for targets with spheroidal geometries, which plays an important role in the field of detection and recognition of submerged elongated targets. In the literature reported in the past, a number of computational techniques were developed to explore acoustic scattering problems by a rigid spheroid under the plane wave incidence, including the separation of variables methods in spheroidal coordinates [42,43], the iterative extended boundary condition method (IEBCM) [44,45], the finite difference time-domain method [46], the finite element method (FEM) [47], and the shape perturbation method [48], to name but a few. However, the above techniques are somewhat subjected to their own weaknesses and applicable circumstances [49].

In the present work, the *T*-matrix method (also called the null-field method, or extended boundary condition method EBCM) is initially extended to compute acoustic scattering by a large aspect-ratio rigid spheroid interacting with an acoustical Bessel beam at arbitrary incidence, with no restriction to the on-axis case treated previously [32]. The *T*-matrix method, as originally conceived by Waterman [50,51], has been demonstrated to be a powerful tool to handle acoustic scattering problems for nonspherical targets, such as elliptic cylinders [52,53], spheroids [54–58] and even the combination of them [59]. The advantage of the *T*-matrix method is to expand all field quantities in terms of a set of spherical functions, which is much convenient from a computational standpoint. The main point of the present method is to obtain the T matrix (transition matrix) that gives a direct relationship between the known expansion coefficients of the incident waves and the unknown expansion coefficients of the scattered field. Moreover, the *T*-matrix formulation allows the computation of scattering problems at a variety of incidence and scattering angles. Therefore, it is anticipated that several novel physical phenomena occurring during the interaction of an acoustical Bessel beam with a large aspect-ratio rigid spheroid with arbitrary orientation may be discovered by numerical computations using this method.

The frame of this article is outlined as follows. In the first part of Section 2, theoretical formulas of the *T*-matrix method for the acoustic scattering by rigid (oblate and prolate) spheroid immersed in fluid are presented briefly. Subsequently, the expansion coefficients of the incident Bessel beam are derived in detail in the second part of Section 2. In Section 3, numerical validation is firstly implemented to verify the correctness of the T-matrix approach for large aspect-ratio rigid spheroids. Then, additional numerical examples are carried out with particular emphasis on the aspect ratio, the half-cone angles, the dimensionless frequency, as well as the incidence angles of the Bessel beam. Finally, some useful concluding remarks are summarized in Section 4.

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