Wave Motion 51 (2014) 986–993

Contents lists available at ScienceDirect

Wave Motion

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

Single Bessel tractor-beam tweezers

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HIGHLIGHTS

- The acoustic radiation force of a finite Bessel beam is derived.
- Conditions are found where the acoustical waves act as a *tractor* beam.
- Numerical predictions are provided using a partial-wave expansion method.

ARTICLE INFO

Article history:
Received 3 November 2013
Received in revised form 28 March 2014
Accepted 30 March 2014
Available online 12 April 2014

Keywords:
Acoustic radiation force
Finite Bessel beam
Acoustic tweezers
Tractor beam
Particle manipulation

ABSTRACT

The tractor behavior of a zero-order Bessel acoustic beam acting on a fluid sphere, and emanating from a finite circular aperture (as opposed to waves of infinite extent) is demonstrated theoretically. Conditions for an attractive force acting in opposite direction of the radiating waves, determined by the choice of the beam's half-cone angle, the size of the radiator, and its distance from a fluid sphere, are established and discussed. Numerical predictions for the radiation force function, which is the radiation force per unit energy density and cross-sectional surface, are provided using a partial-wave expansion method stemming from the acoustic scattering. The results suggest a simple and reliable analysis for the design of Bessel beam acoustical tweezers and tractor beam devices.

1. Introduction

The ability to manipulate and trap particles in a confined space into desired patterns is a critical process in cell separation [1], tissue engineering [2] and biological scaffolding [3–5], the science of materials [6] and metamaterial composites [7], cell microarrays [8,9], and other research areas.

Various modalities for trapping and manipulating particles using tweezers devices exist [10], including optoelectronic, magnetic, electrical, optical and acoustical tweezers (see the references list in Ref. [10]). However, due to some remaining limitations of these tools, significant interest is constantly directed toward the development of versatile, fast and cost-effective particle trapping devices.

Along this line of research, acoustical tweezers have been introduced as one of the most reliable and cost-effective devices, which use the forces of ultrasonic radiation [11] to trap and manipulate particulate matter. Substantial research [10,12–15] has been focused on various applications since the earlier version used counter-propagating waves from two separate ultrasonic probes to form a beam of standing waves and trap microparticles [16].

Most established acoustical tweezers devices use counter-propagating waves [10,12,13,17] to set up standing wave nodes and anti-nodes to trap the particles [7,18–20]. Moreover, experimental [21,22] and theoretical [23–26] research suggested the use of counter-propagating Bessel beams, to trap particles over extended distances. Such methods, however, may require complex equipment for transducer design, and may be time-consuming for calibration purposes. In addition, the counter-propagating (dual-wave) setup often creates multiple trapping points [7,27], which could be problematic when only a single particular region for particle trapping and manipulation is needed in the media.

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http://dx.doi.org/10.1016/j.wavemoti.2014.03.010

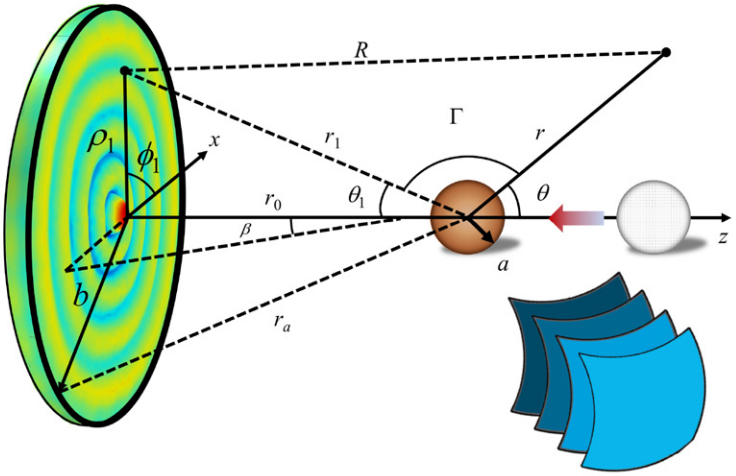

Fig. 1. A finite circular zero-order Bessel beam source with radius b emits acoustical waves, incident upon a spherical particle of radius a centered on its axis of wave propagation. The presence of the sphere causes the incident waves to scatter. The distance r denotes the position from the center of the sphere to an observation point. R denotes the distance from a point on the piston's surface to the observation point, and r_0 is the distance from the center of the radiator to the center of the sphere.

Motivated by the need to further develop faster, simpler and more reliable tools in acoustical tweezers, a *single*-beam of focused progressive waves had effectively produced lateral trapping in the off-axial direction [28]. Moreover, a single-beam particle trapping device with an extended focal region [29] achieved trapping by emulating the behavior of an axicon using a multi-foci air-backed Fresnel lens, while a recent theoretical approach proposes the use of a single piezo-disk radiator with uniform vibration (which is readily available commercially) to accomplish particle entrapment in the near-field zone of the piston source [30].

In contrast to counter-propagating beams, single-Bessel acoustical beams [31,32] have been suggested for particle trapping and tweezing [33–35], which required fabricating a 16-element circular array device by dicing a piezo-ceramic ring, backed with an absorbing layer of mixed epoxy and alumina [34]. Other methods, such as the non-uniform poling technique [31,36], or a Bessel-driven multi-annular transducer [37], have been suggested and proven to produce a finite (limited-diffracting) Bessel beam. Nevertheless, applying such approaches in the design and manufacturing of Bessel acoustical tweezers can be laborious, costly, and may require advanced equipment and extensive hardware development. Therefore, it is of some importance to work out improved and reliable methods for the experimental verification and theoretical predictions of acoustical tweezing capabilities using conventional (commercially-available) ultrasonic probes operating with Bessel modes.

This analysis suggests the use of a standard piezo-disk transducer vibrating *non-uniformly* according to one of its radially symmetric modes [38–43] to generate a zero-order Bessel beam [44] (Fig. 1), having a pressure maximum in amplitude (or intensity) along its center (as opposed to the higher order Bessel beams having an axial null [45]). For these radial modes, there exist vibrations (and subsequent acoustic radiation) in both radial and axial (out-of-plane) directions, which can be in or out of phase depending on the mode order (see Ch. 5 in [46], and the animations in [44]). In the radial direction, there are nodal circles over the thickness of the disk at well-defined radii at which the displacement in the radial direction is zero, and the number of nodal circles increases as the mode order increases [46]. Those can be closely approximated by a normal velocity profile at the surface of the vibrating radiator ($z = 0$) in the form of a cylindrical Bessel function of order zero (denoted by J_0), having a maximum in amplitude at the center of the beam.

In contrast with the studies using Bessel waves of infinite extent [23,47] which carry an infinite amount of energy and thus, are practically and physically unrealizable, the aim here is to investigate the prediction of a pulling (negative) force for particle tweezing using a *single*-Bessel beam generated from a *finite* circular radiator driven at one of its radially-symmetric modes. For particle trapping in real-world applications, this approach may be the most simpler, effective and rapid method for the generation of an ultrasonic Bessel beam of limited-diffraction by exciting the piezoelectric crystal (or ceramic) disk at one of its radially-symmetric vibrational modes, so as to achieve a single Bessel tractor beam tweezers device.

Through numerical simulations, the acoustic radiation force function for a fluid hexane sphere, which is the radiation force per unit energy density and cross-sectional area, is evaluated. The fluid sphere example is of particular interest in various bioengineering/biophysical/(bio)chemical applications, which may closely mimic the behavior of a single cell or a liquid droplet in a Bessel beam. Nevertheless, the analysis can be readily extended to elastic or viscoelastic (layered) spheres [48,49], or shells [50,51], providing their appropriate scattering coefficients are used. In this analysis, the sphere is immersed in an ideal (non-viscous) fluid, and particular emphasis is given on the distance separating the sphere from the Bessel acoustic source r_0, the radius of the transducer b, and the half-cone angle of the beam β. The numerical computations are of