

A review on single-beam acoustical tweezers: From tractor beam to selective trapping[☆]

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ABSTRACT

Single-beam acoustical tweezers show promising prospects in various fields such as biomedical engineering, bubble-based controlled drug delivery, and acoustic material printing for microparticle manipulation and assembly. Acoustic vortices (including cylindrical and spherical types) not only carry pseudo-linear momentum enabling pulling/selective trapping and orbital rotation of particles (at off-axis incidence), but also possess pseudo-angular momentum that induces spinning rotation, thereby substantially enriching the degrees of freedom in acoustical manipulation. This review aims at providing a comprehensive literature on the rapidly developing tool of single-beam acoustical tweezers from the point of view of both theoretical development and representative experimental demonstrations. Furthermore, we discuss the perspectives and ongoing challenges for single-beam acoustical tweezers for applications in several potential fields.

1. Introduction

The selective trapping of a single cell or micro-sized particle is a fundamental technique in biomedical and life sciences, enabling applications such as measuring the mechanical properties of living cells, selecting reproductive cells, and delivering drugs in vivo with high spatial resolution. In general, cell manipulation techniques can be broadly classified into two categories: the contact and non-contact methods. Taking the application of in-Vitro fertilization (IVF) as an example, contact-based manipulation primarily relies on the micropipette techniques which employ pressure gradients to aspirate individual cells [1]. However, this method may damage the cell and cause contamination due to the physical contact. As an alternative, non-contact manipulation techniques based on physical fields such as optics, acoustics, and magnetics have emerged as promising solutions to overcome this limitation. Optical tweezers [2] provide remarkable selectivity and precision, which won the 2018 Nobel Prize in Physics, but their dependence on high-intensity lasers poses a substantial risk of thermal damage to cells [3,4]. Magnetic tweezers have low stiffness due to the weak field gradient. They require magnetic pretagging for objects that are not inherently magnetic. This reduces their applicability in

native biological environments [5]. Acoustical tweezers with the first terminology proposed by Wu [6] can operate without pretagging, offer excellent biocompatibility, and generate stronger trapping forces at equivalent driving power compared to optical tweezers [7–10]. Although acoustical tweezers based on standing waves have been widely studied, their configuration necessitates two transducers or a transducer with a reflector which is not easy to use in clinical trials like the ultrasonic imaging probe. This wave configuration produces multiple equilibrium positions and is helpful for collective manipulation of cells, whereas limiting its application in selective trapping [11,12]. The term of ‘selective trapping’ means that one can trap a targeted particle selectively without disturbing the neighboring particles.

Single-beam selective acoustical tweezers, implemented by placing a single ultrasound source from one side of the target region and capable of individual particle manipulation, provide an effective solution to the above challenges. As most interested particles (for instance, cells) are denser and stiffer than the surrounding fluid medium, they typically exhibit a positive acoustic contrast factor and tend to be trapped at pressure nodes [13,14]. This trapping tendency, however, limits the ability of conventional focused beams to achieve selective trapping

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of an individual cell in three dimensions. To overcome this, special structured wavefields [15–17], such as cylindrical and spherical (or focused) vortices are proposed with their mathematical expressions corresponding to separated variable solutions of the Helmholtz equation in cylindrical and spherical coordinates, respectively [9]. Cylindrical vortices offer two-dimensional lateral trapping but produce exclusively non-restoring axial forces because there is no field gradient in the propagation direction. This kind of single-beam acoustical tweezers induces either pushing or pulling forces (i.e., no axial trapping), with the latter case representing the tractor beam [18,19]. In contrast, spherical vortices have the acoustic intensity gradient in both the lateral and axial directions and can achieve three-dimensional trapping, as first theoretically predicted [20] and then experimentally validated in the water medium [21] by Baresch et al. Furthermore, acoustic vortices also carry the pseudo-orbital angular momentum that can induce spinning motion around the particle's mass center [22]. Note that the orbital rotation of the particle around the beam axis is induced by the acoustic radiation force at the off-axis configuration or the drag force by the acoustic streaming. This unique capability introduces an additional degree of freedom in acoustic manipulation, making force–torque synergistic manipulation an emerging research frontier.

While acoustic vortex tweezers hold the ability for selective trapping, it is limited to assemble a few particles precisely one by one with applications in tissue engineering and particle–particle interaction. The repulsive forces exerted by a single acoustic vortex on particles outside its trapping well currently prevent coordinated multi-target assembly. By employing the synchronized acoustical tweezers [23,24], the destructive interference between two acoustic vortices can be utilized to create an attractive path between two trapped particles, thereby enabling the assembly process.

The paper is organized as follows. Section 2 reviews the development of tractor beams, with a specific focus on theoretical studies of the negative acoustic radiation force (ARF) generated by cylindrical vortices. Section 3 systematically outlines the theoretical and experimental advances in three-dimensional (3D) particle trapping using single-beam focused acoustical tweezers, also addressing the parallel development of acoustic radiation force theory. In Section 4, we present research advances in particle rotation, encompassing both spinning and orbital motion, while also tracing the parallel development of theoretical models for acoustic radiation torque. Section 5 provides an overview of acoustic streaming in single-beam acoustic tweezers. This effect becomes particularly important at high frequencies, where the drag force induced by streaming may exceed the acoustic radiation force. Section 6 reviews theoretical advances in particle assembly based on the interference of two synchronized acoustic vortices. Section 7 discusses future prospects and challenges of single-beam acoustical tweezers. The conclusion is presented in Section 8.

2. Tractor beam

General case: Trapping and scattering with Bessel beams Acoustic pulling forces can be viewed as a special outcome within the broader framework of particle manipulation using structured acoustic beams, for which cylindrical Bessel beams are often adopted as a canonical model due to their nondiffracting beam nature and characteristic “doughnut-shaped” acoustic field structure. When the particle size is comparable to the acoustic wavelength, the radiation force generally requires a rigorous description based on scattering theory under structured beam illumination. In this context, Marston systematically analyzed the scattering behavior of a sphere under Bessel beam illumination [15,25], providing a theoretical framework for evaluating radiation forces in such non-diffracting fields. Subsequent studies [26–30] extended the model to rigid spheres, shells, porous spheres, higher-order helicoidal Bessel beams, and more general non-diffracting beams, further confirming the generality and robustness of structured beam scattering models. Beyond the axial force characteristics, lateral

confinement and trapping stability are equally important in practical manipulation: Fan and Zhang [31] introduced the concept of a stable acoustic tractor beam, emphasizing that robust manipulation requires lateral restoring forces to ensure stably transverse trapping, and established practical design rules for acoustofluidic and particle manipulation applications. Along the propagation direction, a single-sided plane waves typically produces a positive radiation force, as can be directly verified by Eq. (1) [32,33], so particles are commonly transported downstream even when laterally trapped. Under special scattering conditions, however, the axial radiation force can reverse sign and become negative (pulling), which motivates the acoustic tractor beam configurations discussed below.

$$F_{\text{rad}} \propto \sum_{n=0}^{\infty} (n+1) \sin^2(\delta_n - \delta_{n+1}) \geq 0 \quad (1)$$

where n is the partial wave index, δ_n and δ_{n+1} are the real phase shifts corresponding to different order n .

Special case: Acoustic tractor beam. The tractor beam is capable of exerting a pulling force on particles opposite to the direction of acoustic wave propagation, thereby generating a negative axial radiation force (as shown in Fig. 1B). This phenomenon stands in sharp contrast to the conventional radiation force produced by plane waves (as illustrated in Fig. 1A), which typically pushes passive particles away from the source along the direction of wave propagation [34–36]. This counterintuitive phenomenon has been investigated in both acoustics [18,26,27,37] and optics [38–40]. Marston was the first to theoretically demonstrate that a pulling force can arise under specific conditions [18], which laid the theoretical foundation for the acoustic tractor beam. Zhang & Marston later provided the geometric interpretation of this phenomenon, revealing its close connection to the suppression of backscattering [37]. With the continuous advancement of theoretical investigations, experimental validation also achieved a critical breakthrough. Since the generation of ideal Bessel beams is challenging in practice, researchers explored alternative approaches to achieve pulling forces. The theoretical groundwork was laid by Xu et al. [41], who analyzed the pulling force on a particle generated by two interfering plane waves. Building on this, Démoré et al. [19] used plane waves to realize an acoustic tractor beam experimentally for the first time, demonstrating a negative radiation force (also a nonconservative force) directed toward the source on a large triangular target. This achievement marked the transition of the acoustic tractor beam from theoretical prediction to experimental realization. Beyond the tractor beams discussed above, optimized phase modulation in phased arrays enables a single-sided emitter to generate special beams such as bottle beams. These wavefields extend beyond mere pulling, supporting diverse manipulation modalities including acoustic trapping, levitation, translation, and rotation [17,42]. Complementary to fully programmable arrays, recent single-source holographic approaches realize multi-functional manipulation by encoding multiple target fields into one element and switching them via frequency tuning [43].

3. Three-dimensional trapping

As the acoustic counterpart to optical tweezers [44], acoustic focused beams are a natural candidate for the selective three-dimensional trapping and manipulation of individual particles. The group of K.K.Shung first explored the feasibility of particle trapping with a single-beam focused acoustic field using the ray acoustics approach [45, 46]. In the subsequent experimental validation, they successfully achieved lateral trapping of oleic acid lipid droplets using a 30 MHz single-beam focused acoustic field, whereas axial confinement was not demonstrated [47]. Building upon this foundation, the group extended their single-beam approach to a variety of targets including particles, droplets, and human cells, though all demonstrations remained limited to two-dimensional trapping. Notably, the experimental conditions diverged considerably from the assumptions of the ray acoustics model,

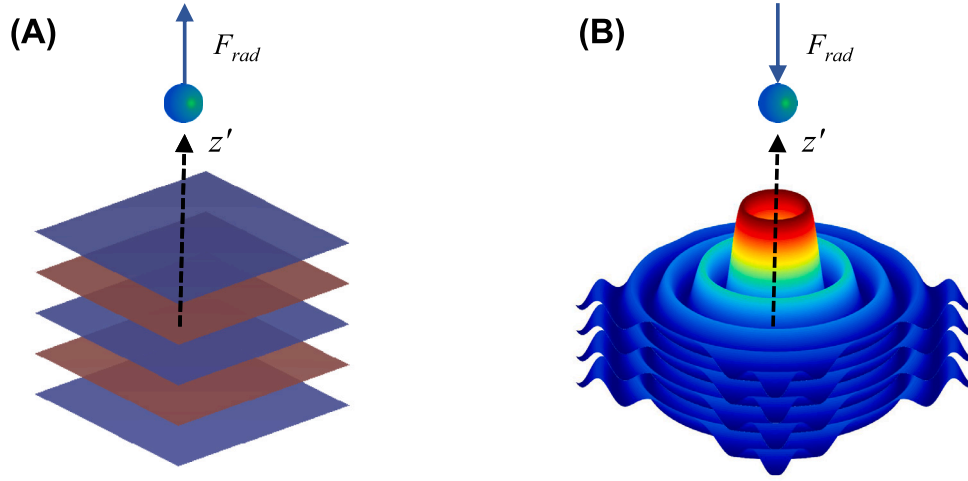


Fig. 1. Schematic of particle pushing in a plane wave and pulling in a tractor beam. (A). The plane wave can only exert a pushing force on a passive particle with $F_{rad} > 0$ as verified in Eq. (1). (B). The acoustic vortex can generate a pulling force on a particle with selected parameters as a tractor beam.

making quantitative comparison between theoretical predictions and experimental results unfeasible [48–50].

To address the theoretical gap in predicting acoustic radiation forces on particles with arbitrary sizes, subsequent studies developed models based on the multipole expansion method (MEM) [51–53] and the angular spectrum method (ASM) [54], respectively, enabling the calculation of 3D radiation forces on arbitrarily sized particles illustrated by arbitrary incident fields. Gong et al. [55] further established the equivalence between these theoretical frameworks, thereby consolidating the foundation for accurate prediction of acoustic radiation forces. Compared with the MEM, ASM is particularly suitable for fields generated by planar transducers with finite aperture [55,56]. The corresponding 3D expressions for the ARF under the ASM framework are given by [54]:

$$F_x = \frac{1}{4\pi^2 \rho_0 k^2 c_0^2} \operatorname{Re} \left\{ \sum_{n=0}^{\infty} \sum_{m=-n}^n C_n \left(-b_{n+1}^{-m} H_{nm} H_{n+1,m-1}^* + b_{n+1}^m H_{nm} H_{n+1,m+1}^* \right) \right\} \quad (2a)$$

$$F_y = \frac{1}{4\pi^2 \rho_0 k^2 c_0^2} \operatorname{Im} \left\{ \sum_{n=0}^{\infty} \sum_{m=-n}^n C_n b_{n+1}^m \left(H_{n,-m} H_{n+1,-m-1}^* + H_{nm} H_{n+1,m+1}^* \right) \right\}, \quad (2b)$$

$$F_z = -\frac{1}{2\pi^2 \rho_0 k^2 c_0^2} \operatorname{Re} \left\{ \sum_{n=0}^{\infty} \sum_{m=-n}^n C_n c_{n+1}^m H_{nm} H_{n+1,m}^* \right\}. \quad (2c)$$

where $C_n = A_n + 2A_n A_{n+1}^* + A_{n+1}^*$, $b_n^m = \sqrt{(n+m)(n+m+1)/[(2n-1)(2n+1)]}$, $c_n^m = \sqrt{(n+m)(n-m)/[(2n-1)(2n+1)]}$, and ρ_0 and c_0 are the density and sound speed in the medium, k is the wavenumber, and “Re” and “Im” represent the real and imaginary part of a complex number. Note that here the partial wave coefficients A_n^m reduce to A_n owing to the spherical shape of the particle. For nonspherical particles, see Eq.(13) from Ref. [55].

Since most particles of our interest (e.g., polystyrene particles and biological cells with a positive acoustic contrast factor) are denser and stiffer than the surrounding host fluid, they tend to be trapped at the local pressure minima. This makes conventional focused beams ineffective for three-dimensional trapping of such particles, which can only 2D trapping under specific resonance conditions [13,14]. To address this issue, Baresch et al. [20] pioneered the concept that specialized wavefields, known as focused acoustic vortices, could achieve three-dimensional trapping with a single beam. In particular, spherical vortex beams have been proposed as a vortex-field refinement to strengthen the axial radiation force, aiming at more robust single-beam trapping of larger particles [57]. Such a wavefield, which is typically generated by transducer arrays [17,58,59] or passive holographic methods [60–64], possesses a phase singularity on the beam axis and a doughnut-shaped

acoustic intensity distribution in the focal plane with (pseudo-) orbital angular momentum [9,20,65,66]. Subsequently, Baresch et al. [21] provided the first experimental demonstration of 3D particle trapping with this field in water, using the gradient force from a 1.15 MHz single-beam focused vortex as shown in Fig. 2A and B. The ability of such focused acoustic fields to trap particles in air was also demonstrated by Marzo et al. [17]. These groundbreaking works paved the way for practical single-beam acoustical tweezers.

A key optimization was introduced by Riaud et al. [67] and Baudoin et al. [68], who improved the complex transducer array proposed by Baresch et al. [21] with a monolithic spiral interdigitated transducer (fabricated using MEMS technology) for selective particle manipulation. The flat and compact architecture of this device enables seamless integration into microscopic and microfluidic systems, providing a milestone for its use as a practical instrument for cells and microparticles. This transducer has achieved highly selective 2D manipulation of living human cells by using high-frequency (tens of MHz) acoustic waves, which provide the requisite cellular-scale wavelengths for a high spatial resolution (as shown in Fig. 2C and 2D) [8]. Subsequently, theoretical studies further confirmed the capability of this transducer for three-dimensional trapping of microparticles and cells, as well as the axial displacement via frequency tuning [69]. Furthermore, a recent theoretical study reveals that by introducing iodixanol solution to reverse the acoustic contrast factor one can achieve the three-dimensional cell trapping with a single-beam focused field, both within and beyond the Rayleigh regime. This finding further unlocks the potential of focused-beam acoustical tweezers, opening a new avenue for 3D cell trapping as similar as the optical tweezers [14].

4. Rotation induced by acoustic radiation force and torque

As shown in Fig. 3, acoustic rotation can be classified into three types based on the underlying mechanism: spinning motion, defined as the rotation of a particle about its own mass center due to acoustic radiation torque (ART) [70,71]; orbital revolution, defined as the motion of a particle orbiting the vortex core driven by azimuthal force [52], can lead to unstable particle trapping [72]; and streaming-induced rotation, caused by the drag torque from acoustic streaming (particularly at high frequencies) [73,74].

Among these, ART is uniquely associated with the angular momentum carried by the wave field, which constitutes the main topic introduced in this section. In optical tweezers, torque can be exerted due to the angular momentum carried by photons. This new degree of

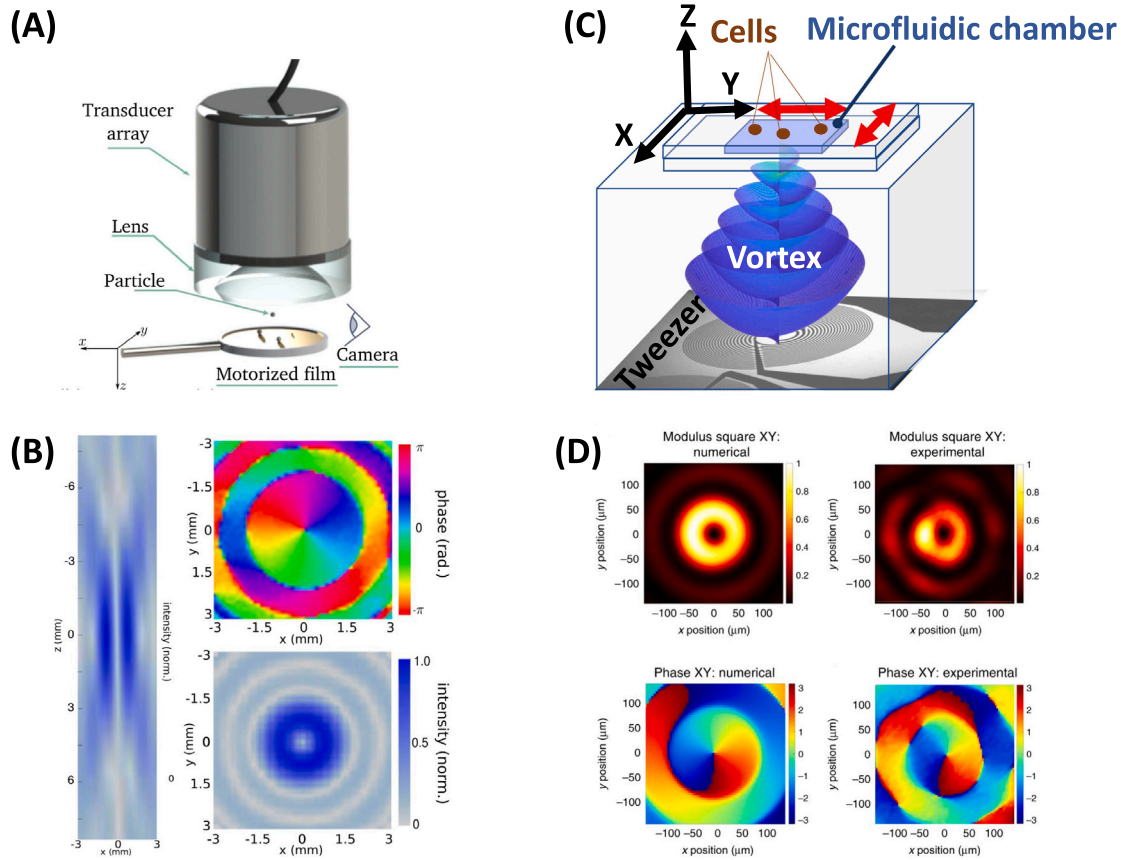


Fig. 2. Schematic of focused acoustic vortices and the acoustic field distribution. (A). Transducer array for the focused vortex at 1.15 MHz with a motorized film for particles immersed in a water tank. (B). The normalized acoustic fields in the propagation plane and focal plane. Reproduced with permission from Baresch et al. *Phys.Rev.Lett.* 116, 024301(2016). Copyright 2016 by the American Physical Society. (C) shows the schematic diagram of the setup for selective cell manipulation using focused acoustic vortex tweezers. (D). Normalized magnitude and phase of the simulated and measured acoustic displacement on the glass slide. Reproduced with permission from Baudoin et al. *Nat.Comm.* 11,4244(2020). Copyright 2020 Author(s), licensed under a Creative Commons Attribution (CC BY) license.

freedom is crucial for the controlled rotation of particles through optical manipulation [75–77]. In acoustics, however, longitudinal waves in fluids do not carry true angular momentum but rather pseudo-angular momentum associated with their momentum flux [59,78]. This pseudo-angular momentum can be transferred to matter and thus gives rise to the ART. In particular, the momentum flux vector of an acoustic vortex offers an additional degree of freedom for particle manipulation [22].

As first established by Maidanik, the ART can be calculated by transferring the surface integral of the time-averaged angular momentum flux tensor from the particle surface to a far field spherical surface centered on the particle's mass center [70]. Based on this, Zhang and Marston [79] derived a compact expression for the axial ART exerted on axisymmetric particles positioned on the axis of an acoustic vortex beam in an ideal fluid, under conditions beyond the paraxial approximation. Their results revealed that the torque is proportional to the absorbed power and the ratio l/ω , written as $T_z = (l/\omega)P_{abs}$. A similar expression was given for the off-axis situation [80], where the acoustic radiation torque can reverse direction [81], representing a rotational analogue to the reversal of acoustic radiation force. In 2012, Silva et al. [82] derived a general expression for the ART on a sphere at an arbitrary position illustrated by an arbitrary sound field using the MEM, which involves spherical wave expansions of both the incident and scattered fields. Meanwhile, Gong et al. employed the T-matrix method to extend these calculations to objects of arbitrary shape [81]. In 2020, Gong et al. [56] established a general and compact theory for calculating three-dimensional acoustic radiation torque on targets

of arbitrary shape, size, and incident sound field based on the ASM as following:

$$T_x = -\frac{\rho_0 \Phi_0^2}{4k} \operatorname{Re} \left\{ \sum_{n=0}^{\infty} \sum_{m=-n+1}^n \overline{b_n^m} \overline{C_n^m} a_n^{m*} a_n^{m-1} \right\}, \quad (3a)$$

$$T_y = -\frac{\rho_0 \Phi_0^2}{4k} \operatorname{Im} \left\{ \sum_{n=0}^{\infty} \sum_{m=-n+1}^n \overline{b_n^m} \overline{C_n^m} a_n^{m*} a_n^{m-1} \right\}, \quad (3b)$$

$$T_z = -\frac{\rho_0 \Phi_0^2}{2k} \operatorname{Re} \left\{ \sum_{n=0}^{\infty} \sum_{m=-n}^n m \overline{D_n^m} a_n^{m*} a_n^m \right\}. \quad (3c)$$

with $\overline{C_n^m} = A_n^{m-1} + A_n^{m*} + 2A_n^{m-1} A_n^{m*}$, and $\overline{D_n^m} = A_n^m + A_n^m A_n^{m*}$. This theory parallels the theoretical framework developed to compute three-dimensional acoustic radiation forces using the angular spectrum method for acoustic scattering solution [54,55]. The developed approach is more practical, especially when the transducer has a finite aperture and generates complex sound fields like acoustic vortices. Based on these developments, Gong and Baudoin later demonstrated the equivalence between MEM- and ASM-based torque theories [55]. From the point of view of experimental implementation, the transfer of orbital angular momentum (OAM) to matter has been studied both in air [72,83] and water [71,73,84]. These lay the foundation for the controlled rotation of particles.

In recent years, increasing attention has been devoted to the synergistic control of acoustic radiation force and torque. Early demonstrations by Baresch et al. [22] confirmed the stable trapping and spinning of elastic particles in a focused vortex beam, providing direct

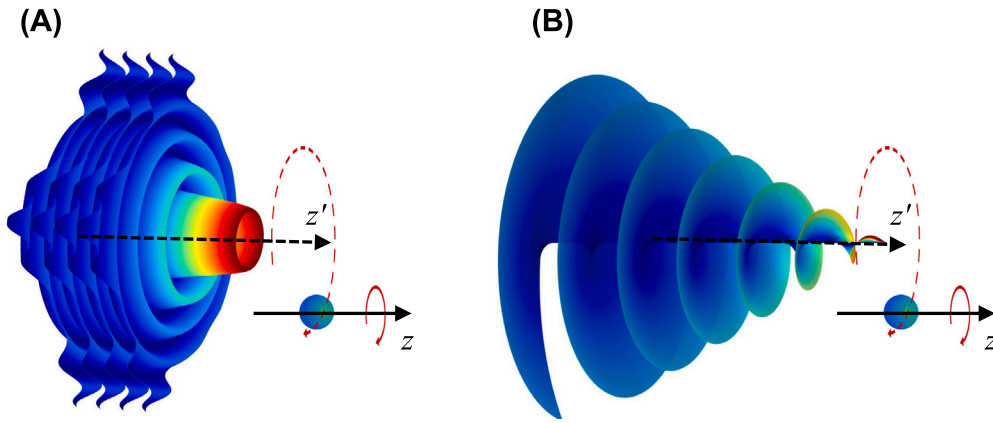


Fig. 3. Schematic diagram of particle rotation in an acoustic vortex field. The dashed trajectory represents orbital rotation around the beam axis, while the solid trajectory indicates spinning rotation over its own axis. Note that the directions shown are only for illustrative purposes, and can be reversed, see 2006 Marston and 2019 Gong. (A). Schematic of particle rotation induced by a cylindrical vortex. (B). Schematic of particle rotation induced by a focused vortex.

evidence of orbital angular momentum transfer in liquids. Building upon this, Li et al. [85] realized a robot-assisted, chirality-tunable acoustic vortex system enabling programmable 3D manipulation and rotation control. More recently, Liu et al. [86] proposed an end-to-end inverse design framework that maps desired acoustic radiation force-acoustic radiation torque vectors to metasurface architectures, enabling programmable acoustical tweezers with simultaneous and customizable manipulation of force and torque.

5. Acoustic streaming in single-beam acoustical tweezers

Single-beam focused acoustic tweezers achieve three-dimensional trapping and manipulation of microparticles via acoustic radiation forces [13]. Because the characteristic size of the target is typically comparable to the acoustic wavelength, micrometer-scale manipulation requires higher frequencies. However, increasing frequency enhances acoustic attenuation and induces acoustic streaming. The resulting streaming-driven drag force tends to advect particles along the direction of energy propagation, thereby competing with the trapping effect of the radiation force. This competition is particularly critical in the axial direction, where the restoring stiffness is typically weaker. As a result, acoustic streaming often becomes a primary limitation for stable three-dimensional trapping. Consequently, in high-frequency single-beam acoustic tweezers, acoustic streaming must be considered alongside radiation forces in both design and performance evaluation [87–89]. Recent designs further suggest that, in carefully engineered single-beam fields, streaming can be leveraged rather than merely mitigated [90].

Acoustic streaming is broadly classified into boundary streaming (or Rayleigh/Schlichting streaming) [91,92] and bulk streaming (or Eckart streaming) [93]. Boundary streaming arises from viscous dissipation within near-wall boundary layers under the no-slip condition [94], whereas bulk streaming originates from acoustic attenuation in the fluid interior [93]. In free-field single-beam configurations with focal regions far from solid boundaries, bulk streaming is typically dominant [95]. In contrast, boundary streaming may substantially alter local flow fields in confined geometries, such as microchannels or at droplet interfaces [96,97]. From a design standpoint, the objective is not to maximize radiation force alone, but to identify a parameter regime in which the restoring radiation force exceeds the streaming-induced drag force, thereby ensuring stable three-dimensional trapping [87,88].

Acoustical vortices carry pseudo-angular momentum, which can be partially transferred to the fluid through viscous attenuation, giving rise to vortex-induced streaming with a controllable topology. Early analyses established the order of magnitude of this streaming [73].

Building on Eckart streaming theory, a complete treatment for cylindrical Bessel vortices showed that the mean flow naturally decomposes into a poloidal flow and a toroidal (azimuthal) flow, and that the on-axis behavior can switch between attractor and repeller regimes depending on confinement and topological charge [74]. Subsequent experiments directly confirmed the emergence of the toroidal component [84] and further demonstrated that a one-sided focused vortex can simultaneously drive downstream pushing and axial rotation near the focus [22]. For single-beam focused acoustic tweezers, these results imply that vortex-induced streaming is a tunable 3D transport mechanism whose azimuthal and axial drags should be evaluated alongside radiation force stiffness when predicting trapping stability and particle trajectories, and can be deliberately exploited for flow patterning and fluid manipulation when desired [98].

6. Precise assembly with synchronized acoustical tweezers

In recent years, the increasing demand for single-sided and highly selective manipulation of microparticles has drawn significant attention to acoustic vortex tweezers, owing to their superior spatial resolution and non-contact nature. However, the characteristic high-intensity annular potential barrier of acoustic vortices often forms repulsive rings that hinder the approach and assembly of multiple particles, posing a major challenge for selective particle–particle interaction as shown in Fig. 4(A).

To overcome this limitation, Gong and Baudoin [23] proposed the concept of synchronized acoustical tweezers. In a two-dimensional configuration, targeted particles are separately trapped at the vortex cores of two in-phase acoustic vortices. Through lateral destructive interference between adjacent vortices, a continuous low-pressure corridor is formed between the vortex centers, enabling particle convergence driven predominantly by acoustic radiation forces as shown in Fig. 4(B). The expression for the acoustic radiation force acting on a Rayleigh particle during the assembly process is given by Eq. (4) [Ref. [24]]:

$$\mathbf{F} = -V_0 \left\{ \nabla \left[f_1 \left(\frac{|p|^2}{4\rho_0 c_0^2} \right) - f_2 \left(\frac{\rho_0 |\mathbf{v}|^2}{4} \right) \right] - \frac{(ka)^3}{3} \left[\left(f_1^2 + \frac{2f_1 f_2}{3} \right) \text{Re} \left(\frac{k}{2c_0} p \mathbf{v}^* \right) - \frac{f_2^2}{3} \text{Im} \left(\frac{\rho_0}{2} \mathbf{v} \cdot \nabla \mathbf{v}^* \right) \right] \right\} \quad (4)$$

where $V_0 = 4/3 \pi a^3$ is the particle volume, a is the radius, $f_1 = (1 - \kappa_p/\kappa_0)$ is the monopolar acoustic contrast factor related to the particle isotropic expansion/compression with κ_p and κ_0 the compressibility of the particle and fluid, $f_2 = 3(\rho_p - \rho_0)/(2\rho_p + \rho_0)$ is the dipolar acoustic contrast factor related to the particle back and forth translation with

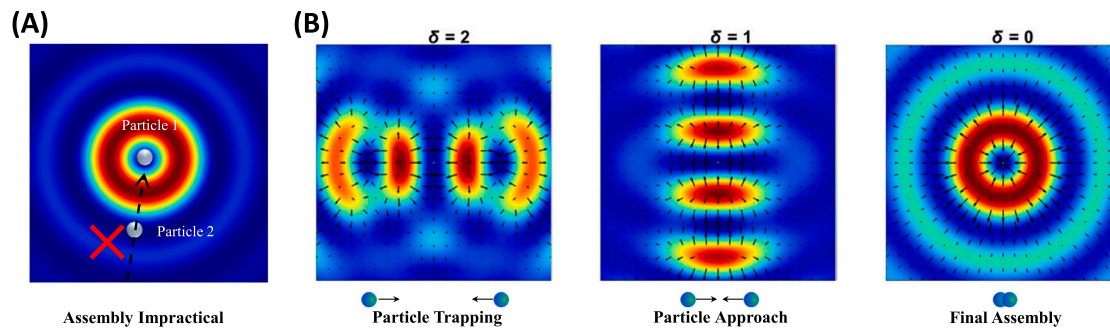


Fig. 4. Schematic diagram of particle assembly using synchronized acoustical tweezers. (A). Assembly failure due to repulsive forces from a single acoustic vortex. (B). Successful assembly via two interfering acoustic vortices. The parameter δ represents the separation between two vortices (see Ref. [23] for details). Reproduced with permission from Zhixiong Gong et al. *Phys.Rev.Applied.* 12, 024045(2019). Copyright 2019 by the American Physical Society.

ρ_p and ρ_0 the density of the particle and fluid respectively, p and \mathbf{v} are the complex pressure and velocity of the incident acoustic fields, and the superscript “*” stands for the complex conjugate.

By incorporating a force balance model between Stokes drag and radiation force, the authors further established a practical assembly velocity criterion applicable in the Rayleigh scattering regime. This concept was later extended by Gong and Baudoin [24] to the 3D case with two synchronized spherical vortex beams, which provide stable assembly from either the lateral or the axial directions.

As for the engineering implementation, Ding et al. [99] proposed a practical scheme using a single-sided ring transducer array to generate multiple off-axis acoustic vortices arranged in a centrosymmetric pattern. By introducing a three-step phase reversal strategy, they engineered successive low-pressure pathway networks forming regular polygonal and multi-armed star configurations prior to convergence. This approach preserves the structural simplicity of single-sided setups while enhancing the programmability and robustness of multi-particle 2D assembly, and demonstrates potential for extension to non-axisymmetric 3D scenarios. A recent work demonstrated another practical method for particle assembly with the tilted synchronized acoustical tweezers with vortex beams at the oblique incidence [100]. While multi-source holographic superposition has enabled one-step volumetric 3D assembly in standard containers [101], synchronized single-beam tweezers target programmable, stepwise assembly and trajectory control with minimal hardware, which is particularly attractive for compact and open configurations.

7. Perspectives and challenges

Single-beam acoustical tweezers, with their non-contact nature and high selectivity, are suitable for a wide range of biomedical and microfluidic applications. Like other acoustical tweezers [7,102,103], single-beam acoustical tweezers offer excellent biocompatibility. However, their unique wave structure provides distinct advantages, enabling diverse biomedical applications such as precise force probe [104,105], cell deformability analysis [106], thrombolysis [107], manipulation of marine microorganisms [108] and targeted drug delivery [109–111].

Despite the widespread use of single-beam acoustical tweezers in cell biology, there are still several practical challenges as obstacles for engineering applications. The first challenge lies in the accurate modeling of single-beam acoustical tweezers. From the theoretical perspective, it is necessary to establish a coupled multiphysics framework incorporating acoustic, hydrodynamic, and thermal effects in order to comprehensively evaluate particle trapping behavior and biosafety. In particular, at high frequencies, acoustic streaming induced by wave attenuation can generate significant fluid drag forces that may alter or even destabilize particle trapping. Therefore, developing a unified model that simultaneously accounts for acoustic radiation forces,

streaming-induced drag force, and thermal effects is essential for accurately predicting particle dynamics in single-beam acoustic tweezers. Experimentally, however, only 2D selective cell trapping has been achieved [8], while 3D free-space trapping has yet to be realized. This limitation currently prevents single-beam acoustical tweezers from assembling cells one by one into three-dimensional structures, as demonstrated with optical tweezers for atoms [112]. Furthermore, tightly focused beams can trigger nonlinear effects such as higher harmonic generation [113,114], which may subsequently modulate acoustic streaming velocities [115]. And they also cause localized heating that raises the issue of biocompatibility [8,116,117]. Thus, developing systematic multiphysics models that reliably predict system behavior under realistic conditions remains an essential direction for future research.

The second challenge is the robust generation of acoustic fields within complex environments in-vivo such as high heterogeneity [118,119], time-varying dynamics [120], and significant inter-individual variability [121]. These factors collectively disturb the intended acoustic wavefronts, leading to possible phase aberration, focal distortion, and energy loss. Consequently, accurately modeling wave propagation under such conditions remains a difficult task. The fidelity of these models directly governs the feasibility of translating single-beam acoustical tweezers from well-controlled in vitro settings to clinically relevant in vivo applications, where predictability and stability are essential for effective and safe operation.

8. Summary

This review has systematically reviewed the theoretical development and main milestones of experimental demonstrations of the single-beam acoustical tweezers with the corresponding physical mechanisms, including the tractor beams and focused acoustic beams (mainly focused vortex). The review has introduced the general theory of 3D acoustic radiation force and torque without limitation on the parameters of particle and acoustic field, and also the expression for the acoustic radiation force for Rayleigh particles with the configuration of synchronized acoustical tweezers.

The translation of these theories into biomedical applications has been explored extensively, highlighting their important role in selective trapping and assembly of cells and microparticles. While significant progress has been made, several key challenges remain—particularly in the modeling of nonlinear acoustic propagation in complex media, achieving robust 3D manipulation in dynamic environments, and integrating acoustical tweezers with multimodal sensing and imaging systems. Addressing these challenges will be critical for the continued evolution of acoustical tweezers in clinical applications. As the field is rapidly developing with several convincing experimental demonstrations, the single-beam acoustical tweezers hold tremendous promise for expanding the toolbox for non-contact, label-free manipulation in biomedicine, materials science, and beyond.

CRediT authorship contribution statement

Shiyu Li: Writing – review & editing, Writing – original draft, Data curation, Conceptualization. **Liwei Chen:** Writing – original draft, Visualization, Data curation. **Yicheng Feng:** Writing – original draft, Data curation. **Xuan Cheng:** Writing – original draft, Data curation. **Zhixiong Gong:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Zhixiong GONG reports financial support was provided by National Natural Science Foundation of China. Shiyu Li, Liwei Chen, Yicheng Feng, Xuan Cheng, Zhixiong Gong reports a relationship with Shanghai Jiao Tong University that includes: employment. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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