

Midair Single-Sided Acoustic Levitation in High-Pressure Regions of Zero-Order Bessel Beams

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Acoustic levitation enables noncontact manipulation using sound waves. While conventional methods entrap particles at pressure nodes (zero-pressure region surrounded by high pressure), we demonstrate stable acoustic levitation and translation in midair within a high-pressure axial core of a zero-order Bessel beam for the first time. The trap operates at a long working distance, up to 397 mm (46.6λ), supports simultaneous multiparticle levitation, and maintains stability over obstacles. Our work establishes a new paradigm for single-sided acoustic manipulation in midair.

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Introduction—Acoustic levitation has emerged as a key technique for noncontact manipulation, with applications spanning from laboratory automation [1–4], volumetric displays [5–7], to additive manufacturing [8–11]. Most of these implementations rely on standing wave configurations, in which the behavior of subwavelength particles (Rayleigh regime) is governed by the acoustic contrast arising from differences in compressibility and density between the particle and the surrounding medium. In a standing wave in air, virtually all particles are consistently trapped at the pressure nodes surrounded by high pressure regions [12]. Single-sided levitators implement the same principle by generating twin, vortex, and bottle traps that enclose a central minima with high-pressure regions [13–16].

While entrapment of Rayleigh-sized particles at pressure nodes is a general consensus in midair levitation, recent theoretical studies have predicted the possibility of trapping particles within high-pressure antinodes in midair. Fan and Zhang, for example, theoretically investigated transverse (2D) trapping in a zero-order Bessel beam, a field with a high-pressure axial core, predicting transverse stability is governed by an interplay between the beam’s cone angle and

particle-to-medium ratios of density and bulk modulus [17]. The predicted transverse restoring force was later experimentally demonstrated with a tethered sphere [18]. Trapping at pressure antinodes has also been demonstrated for wavelength-scale droplets at a liquid-liquid interface, beyond the Rayleigh regime considered here [19]. In airborne standing waves, a particle-size effect has also been shown to trap spheres beyond the Rayleigh regime off axis, near pressure antinodes [20]. The sound pressure field of a zero-order Bessel beam propagating along a z axis is given by [21–25]

$$p(r, z, t) = P_A J_0(kr \sin \beta) e^{j(kz \cos \beta - \omega t)}, \quad (1)$$

where P_A is the amplitude, J_0 is the zero-order Bessel function of the first kind, k is the wave number, ω is the angular frequency, β is the cone angle defined as the angle between the conical wave front and the transverse xy plane, and $r = \sqrt{x^2 + y^2}$ is the radial coordinate. Reference [17] showed that the 2D transverse stability is governed by a beam-parameter (β), that determines the condition for particles to be trapped at high-pressure regions in air. More recently, the trapping analysis has been further extended using a Born approximation framework [26]. Axially, such high-pressure beams exert a propulsive force sufficient to counteract gravity. However, extending the transverse (two-dimensional) stability to achieve stable three-dimensional levitation has remained an experimental challenge. This difficulty was described by Marzo *et al.*, who characterized levitation at an acoustic focus (high pressure region) as an experimentally unstable theoretical possibility [13], a finding that we replicated (Figs. S3, S4, and Movie S1

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in Ref. [27]). In general, although theoretical models allow for levitation at high-pressure regions, experiments to date show particles levitating only at low-pressure nodes.

In this Letter, for the first time, we experimentally demonstrate three-dimensional acoustic levitation within the high-pressure axial core of a zero-order Bessel beam in midair [Fig. 1(a)]. The transverse confinement arises because, below a critical cone angle (β_c), the velocity-gradient contribution to the Gor'kov potential [12,37] overcomes the competing pressure-gradient term for a solid particle in air, producing a restoring force toward the beam axis [17,18,26] (see End Matter for detail). Combined with an upward axial radiation force [17,38,39] that counteracts gravity, the net force forms a stable three-dimensional trap. This result establishes a novel mode of acoustic levitation distinct from the entrapment in planar standing waves and conventional single-sided twin or vortex traps. It supports real-time three-dimensional position control, simultaneous levitation of multiple particles, and the levitation of nonspherical objects, demonstrating the general applicability of the trapping mechanism. The levitation capability remains intact through a physical obstruction due to the Bessel beam's diffraction-free and self-healing ability [40,41]. Furthermore, the axial high pressure remains confined,

extending the working distance from 67 mm (7.9λ) in existing single-side traps to 397 mm (46.6λ) with the Bessel beam. These findings open new pathways for both fundamental studies and practical applications of long-range acoustic manipulation in an open environment, free from the enclosures of standing wave configurations.

Methods—The zero-order Bessel beam is generated using a 16×16 phased array of transducers (PAT, Murata MA40S4S, 40 kHz) known as SonicSurface [46], as shown in Fig. 1(a). The center of the array surface is defined as the origin (x, y, z) = (0, 0, 0). The phase ϕ_i of each transducer at position (x_i, y_i, z_i) is given by [47,48]:

$$\phi_i = -k(\sqrt{x_i^2 + y_i^2} \sin \beta - z_i \cos \beta). \quad (2)$$

The beam was electronically steered by applying a virtual rotation to the transducer coordinates [47]. Given the proportionality between the sound pressure and input voltage V_{in} [49], we characterize the beam amplitude using V_{in} , where the source pressure amplitude of a single transducer P_0 is directly proportional to V_{in} as $P_0 = 0.221V_{\text{in}}$, with the transducer conversion factor given in units of Pa V^{-1} at 1 m from the transducer [see Eq. (7) in Ref. [27]]. For example, for $V_{\text{in}} = 8$ V in Fig. 1, P_0 is 1.768 Pa at 1 m, which creates

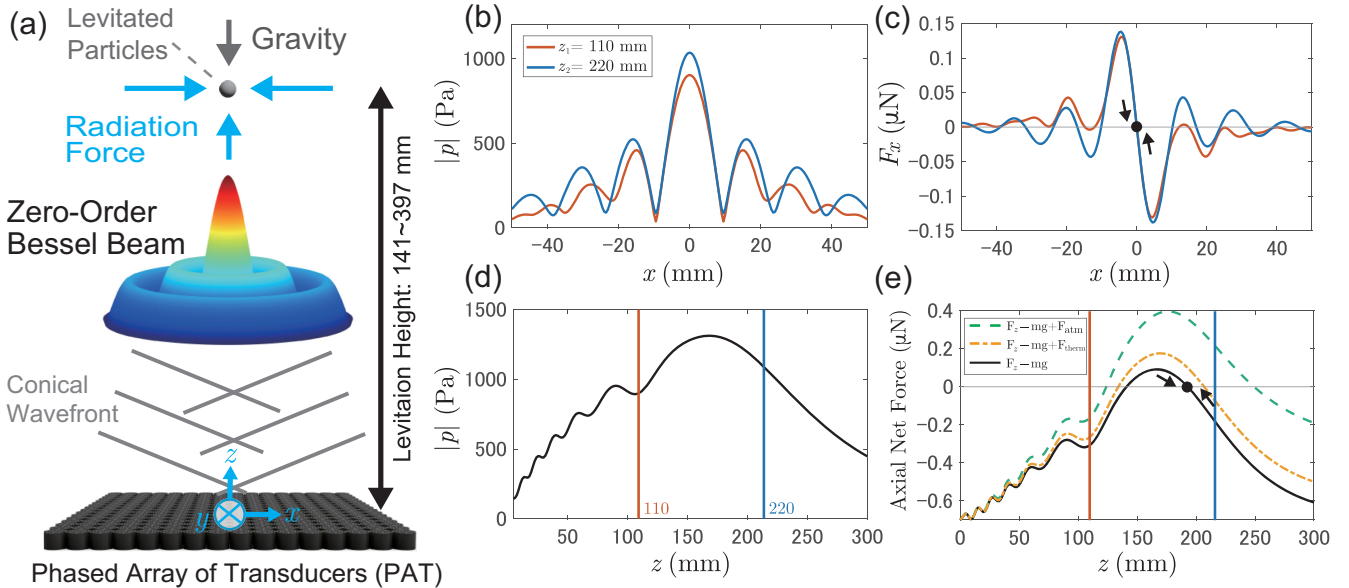


FIG. 1. (a) Illustration of particle levitation at the central core of a zero-order Bessel beam. The beam is generated using a phased array of transducers (PAT). The acoustic radiation force acts as a transverse restoring force and an upward pushing force (blue arrows), while gravity acts downward. The origin (x, y, z) = (0, 0, 0) is defined at the center of the PAT surface, with the z axis oriented normal to the PAT in the direction of beam propagation. Because of the side-view camera configuration, all experimental particle positions are reported as two-dimensional x - z planar projections. (b)–(e) Calculated acoustic pressure field of a zero-order Bessel beam from the PAT ($\beta = 20^\circ$, $V_{\text{in}} = 8$ V) and the radiation force on an expanded polystyrene (EPS) sphere (radius $a = 0.75$ mm, $(a/\lambda) = 0.088$, Rayleigh regime). (b) Transverse and (d) axial pressure profiles. (c) Transverse force F_x . For the axial plots (d) and (e), solid vertical lines indicate the two evaluation planes, $z_1 = 110$ mm (red) and $z_2 = 220$ mm (blue, near the experimental levitation height). (e) Net axial force. The black line shows the balance between radiation force and gravity. The orange and green dashed lines include the drag from acoustic streaming calculated with thermoviscous [42] and atmospheric [43] attenuation models, respectively. The range between these two models is consistent with experimentally observed streaming effects [44,45].

a maximum pressure of 1312 Pa at the core. Acoustic pressure field measurements verified that the experimental beam profile matches well with the numerical predictions (Fig. S5 in Ref. [27]). The particle motion was recorded from the side using a camera (Fig. S1 in Ref. [27]); therefore, particle positions are reported as two-dimensional x - z planar projections. We used an expanded polystyrene (EPS) sphere of radius $a = 0.75$ mm [$(a/\lambda) = 0.088$], similar in scale to particles commonly employed in previous midair levitation experiments [5,6,13,50]. The particle density was $\rho_p = 40.4$ kg m $^{-3}$ and unless otherwise stated, this particle was used throughout the experiments.

Results—To evaluate the levitation capability, the acoustic radiation force on an EPS sphere was numerically calculated using the Andersson and Ahrens method, which utilizes spherical harmonic expansion of the PAT-generated zero-order Bessel beam ($\beta = 20^\circ$) with compressible-sphere scattering coefficients [27,51–53]. The calculations were performed at two axial positions chosen to bracket the on-axis pressure maximum, $z_1 = 110$ mm (12.9λ) and $z_2 = 220$ mm (25.8λ). As shown in Figs. 1(b) and 1(c), the transverse force F_x at both positions is restoring, directed toward the beam axis ($x = 0$) despite an on-axis pressure maximum. This restoring force provides lateral confinement over ranges of approximately 0 ± 12.1 mm (1.42λ) at z_1 and 0 ± 10.2 mm (1.20λ) at z_2 . Figure 1(d) plots the axial pressure profile along the central axis ($x = y = 0$), and Fig. 1(e) plots the corresponding axial net force, which indicates an equilibrium at $z \sim 192$ mm (22.5λ) where the upward acoustic radiation force balances gravity. This axial balance between the upward radiation force and gravity, combined with the lateral confinement, forms a full three-dimensional trap. The axial restoring force remains directed toward the equilibrium for positions $z \gtrsim 141$ mm (16.5λ). A detailed force profile in the xz plane is provided in Fig. S6 of Ref. [27]. At the equilibrium

point ($z = 192$ mm), the axial stiffness, 6.57 $\mu\text{N m}^{-1}$, is an order of magnitude lower than the lateral stiffness, 70.4 $\mu\text{N m}^{-1}$, similarly to single-sided twin and vortex traps [13].

To experimentally validate the trapping capability, we used a zero-order Bessel beam with $\beta = 20^\circ$ (see Movie S2, Fig. S10 in Ref. [27]). In all 15 trials, a particle was stably levitated for the entire 60 s observation period. During these trials, the particle's axial coordinate fluctuated between 206 ± 8 mm and 234 ± 2 mm, with a mean levitation height of 220.4 ± 0.8 mm. Simultaneously, it exhibited transverse fluctuations over a range of ± 2.9 mm. The particle also exhibited fluctuations in equilibrium heights within its axial range (see details in later discussions).

The levitation capability of the Bessel beam is not limited to spherical objects, and levitation can also be performed with a nonspherical dried tea leaf (approximate diameter, 0.8 mm; $V_{\text{in}} = 16$ V; maximum sound pressure, 2623 Pa; Fig. S11(a) and Movie S3 in Ref. [27]), a flat piece of silica aerogel [Classic SilicaTM Disc, Aerogel Technologies, LLC; major axis, 2.3 mm; $V_{\text{in}} = 8$ V; maximum sound pressure, 1312 Pa; Fig. S11(b) and Movie S4 in Ref. [27]], and a single disk formed from coalesced potato starch powder (approximate diameter, 1.3 mm; $V_{\text{in}} = 15$ V; maximum sound pressure, 2459 Pa; Movie S5 in Ref. [27]).

We explored the horizontal translation of particles by tilting the Bessel beam. Specifically, the tilt angle was modulated according to $\theta_{\text{tilt}}(t) = A_{\text{tilt}} \sin(2\pi f_{\text{tilt}} t + \pi)$, where t represents time, $A_{\text{tilt}} = 10^\circ$ is the maximum tilt angle, and $f_{\text{tilt}} = 0.35$ Hz. Using these parameters, the particles were translated horizontally at a speed of approximately 5.7 cm s $^{-1}$ [Figs. 2(a)–2(c) and Movie S6 in Ref. [27]]. This modulation also introduced slight vertical oscillations on the order of centimeters [Figs. S12(a) and S12(b) in Ref. [27]].

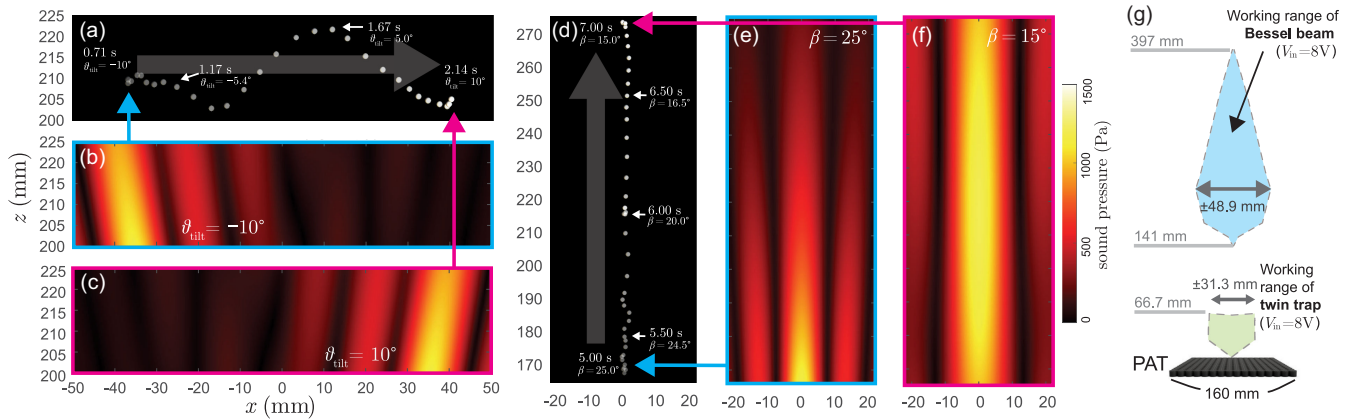


FIG. 2. Particle translation by (a)–(c) horizontal beam tilting (θ_{tilt} from -10° to 10°) and (d)–(f) vertical cone angle modulation (β from 25° to 15°). The experimental trajectories in (a) and (d) are composites of images taken every 0.05 s, visualized with increasing opacity (30%–100%) to indicate the temporal evolution of the trajectory. The corresponding simulated pressure profiles ($V_{\text{in}} = 8$ V) are shown in (b), (c) and (e), (f); the maximum sound pressures are 1270 Pa in (b), (c), 1399 Pa in (e), and 1202 Pa in (f). (g) Experimental comparison of the working ranges for a Bessel beam and a conventional twin trap (average of five trials).

Two methods were considered for the vertical translation: modulation of the cone angle (β) of the Bessel beam and modulation of the input voltage (V_{in}) to the PAT. We employed the cone angle modulation method over the voltage modulation method because of its higher stability in preliminary experiments. This control is achieved through the monotonic dependence of the axial radiation force on the cone angle β . Decreasing β enhances the upward force and raises the particle's equilibrium position, whereas increasing β reduces the force and lowers it [Eq. (12) in Ref. [17]]. The cone angle was modulated according to $\beta(t) = A_\beta \sin(2\pi f_\beta t + \pi) + \beta_{\text{offset}}$, where $A_\beta = 5^\circ$ and $f_\beta = 0.25$ Hz are the amplitude and frequency of the cone angle modulation, respectively, and $\beta_{\text{offset}} = 20^\circ$ is the offset cone angle. Using these parameters, the particles were translated vertically at a speed of approximately 4.3 cm s^{-1} [Figs. 2(d)–2(f), Figs. S12(c) and S12(d), and Movie S7 in Ref. [27]].

By combining the horizontal and vertical translation techniques described above, we experimentally determined the working range achievable with the Bessel beam (see Methods in Ref. [27]). As shown in Fig. 2(g), the particles were translated over a horizontal range of ± 48.9 mm ($\pm 5.73\lambda$) and a vertical range of 141–397 mm ($16.5 - 46.6\lambda$). For comparison, a conventional twin trap using the same PAT under identical conditions ($V_{\text{in}} = 8$ V) was limited to a horizontal range of ± 31.3 mm ($\pm 3.67\lambda$) and a maximum height of 66.7 mm (7.82λ), highlighting the significantly extended working range of our approach. The calculated maximum sound pressure amplitudes ranged from 1120 to 1890 Pa for the twin trap and from 1080 to 1410 Pa for the Bessel beam (Tables S1 and S2 in Ref. [27]), confirming that the extended working distance is not a consequence of higher acoustic power. Note that independently of the sound pressure level, the working distance of the twin trap is constrained because the transverse radiation force becomes repulsive at longer distances.

We further demonstrate the trapping of multiple particles by generating multiple Bessel beams from a single PAT. This was achieved using an acoustic Dammann grating, a binary phase hologram used for beam replication in both optics [54–56] and, more recently in acoustics [57]. The grating inverts the phase by π for transducers where $0.1A < |x_i| < 0.3A$ [$A = 160$ mm is the array size, Fig. S2(a) in Ref. [27]], which creates two distinct beams. With a cone angle of $\beta = 20^\circ$ and an input voltage of $V_{\text{in}} = 13$ V (maximum sound pressure of 1444 Pa), two particles were simultaneously levitated in the cores of the beams [Fig. 3(a) and Movie S8 in Ref. [27]]. The two particles were trapped at time-averaged (20 s) equilibrium positions of $(x, z) = (-26.8, 227)$ mm (left) and $(32.3, 225)$ mm (right). Their respective positional fluctuations spanned ± 6.3 and ± 6.5 mm in the x direction, and ± 16.8 and ± 21.4 mm in the z direction.

A vertical alignment of levitated particles can be demonstrated using a bottle trap configuration. This approach

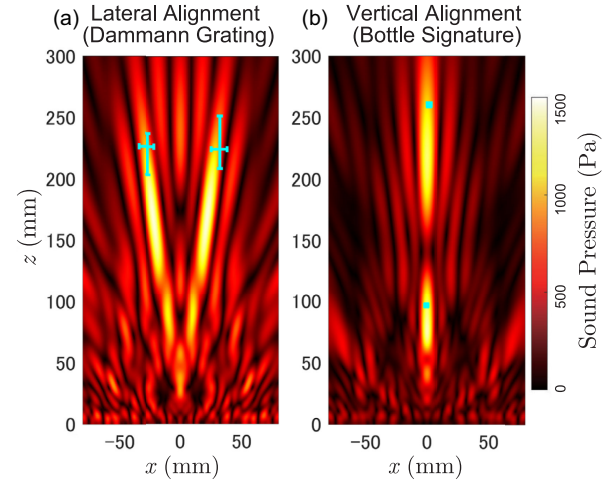


FIG. 3. Simultaneous levitation of multiple particles. (a) Parallel trapping of two particles (left: $a = 0.79$ mm, $\rho_p = 32.3 \text{ kg m}^{-3}$; right: $a = 0.79$ mm, $\rho_p = 31.6 \text{ kg m}^{-3}$) in replicated Bessel beams with Dammann grating. (b) Vertically aligned trapping of two particles (top: $a = 0.77$ mm, $\rho_p = 35.5 \text{ kg m}^{-3}$; bottom: $a = 0.77$ mm, $\rho_p = 34.3 \text{ kg m}^{-3}$) in separated zones with bottle signature. The cyan lines indicate the range of positional fluctuations, which is significantly smaller for the vertically aligned trap.

splits the high-pressure core along the beam axis into two distinct trapping zones by creating a central low-pressure region. The bottle phase signature was implemented by inverting the phase by π for transducers where $\sqrt{x_i^2 + y_i^2} > 0.35A$ [Fig. S2(b) in Ref. [27] and Ref. [13]]. With an input voltage of $V_{\text{in}} = 9$ V and a cone angle of $\beta = 21^\circ$ (maximum sound pressure of 1400 Pa), two particles were simultaneously levitated in these vertically separated zones [Fig. 3(b) and Movie S9 in Ref. [27]]. Their time-averaged (20 s) equilibrium positions were $(x, z) = (-0.588, 96.7)$ mm (bottom) and $(1.59, 261)$ mm (top), with respective positional fluctuations spanning ± 0.92 and ± 1.66 mm in the x direction, and ± 0.86 and ± 1.65 mm in the z direction.

We further demonstrate acoustic levitation beyond a physical obstruction, an application that builds on the diffraction-free and self-healing nature of a Bessel beam that enables them to maintain their pressure profile after an obstacle [41]. Boundary element method (BEM) simulations [58] with the AcousTools library [59] show the clear beam reconstruction of the axial high-pressure core for a $\beta = 20^\circ$ zero-order Bessel beam obstructed by a 50 mm cube at $z_1 = 110$ mm [Fig. 4(a)]. This prediction was confirmed experimentally: with an input voltage of $V_{\text{in}} = 14$ V (maximum sound pressure of 1417 Pa above the obstacle), a particle was successfully levitated in the reconstructed beam [Fig. 4(b) and Movie S10 in Ref. [27]]. The particle was maintained at a time-averaged (20 s) equilibrium position of $(x, z) = (-0.652, 267)$ mm, with positional fluctuations spanning ± 3.3 mm in the x direction and ± 20.1 mm in the z direction.

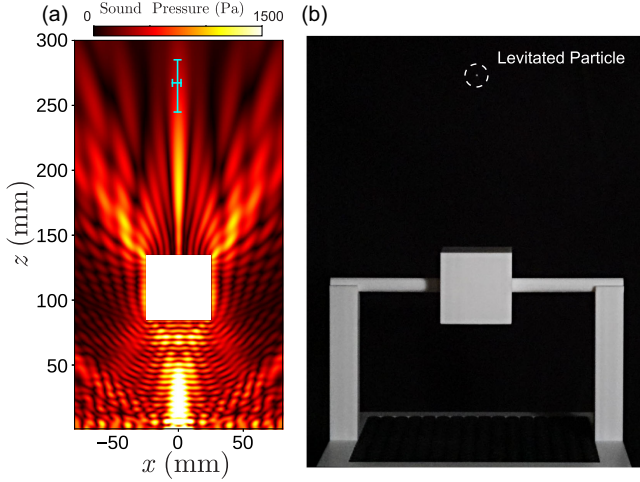


FIG. 4. Experimental demonstration and numerical simulation of levitation beyond an obstacle. (a) Simulated sound pressure field using BEM, showing the reconstruction of the Bessel beam profile beyond the obstacle. The mesh size for BEM was set to approximately $(\lambda/11)$. The cyan lines indicate the range of positional fluctuations. (b) Photograph of a particle levitated above the obstacle.

Discussion—We have experimentally demonstrated stable three-dimensional acoustic levitation within the high-pressure axial core of a zero-order Bessel beam. Here, we further explored the contribution of the various forces.

First, the radiation force model alone predicts a levitation height of $z = 192$ mm, whereas particles were observed to levitate at 220.4 ± 0.8 mm. This difference was reduced by accounting for the upward drag from acoustic streaming. Our numerical simulations predict acoustic streaming velocities between 0.198 m s^{-1} (thermoviscous model) to 0.493 m s^{-1} (atmospheric model), depending on assumed attenuation model at the experimental levitation height ($z_2 = 220$ mm). Indeed, our simulations incorporating this streaming effect predict an equilibrium range of 207–249 mm, in agreement with our experimental observations [Fig. 1(e) and Fig. S9 and Methods in Ref. [27]]. Thus, acoustic streaming is considered to be non-negligible contributor to the final particle position in axial direction.

As predicted by Gor'kov potential [27,37], a restoring force is generated in the transverse direction when the cone angle β is below a critical threshold $\beta < \beta_c$. For an ideal beam with an infinite aperture, this threshold is calculated to be $\beta_c = 26.8^\circ$ for an EPS sphere in air [Eq. (9) in Ref. [17]]. Under this condition, a dominant velocity-gradient term of Gor'kov potential overcomes the competing pressure-gradient term, enabling confinement along the beam axis (see End Matter for derivation). The trapping mechanism is not specific to the PAT architecture; stable levitation was independently achieved using a simplified conical transducer array ($\beta = 25^\circ$) driven in-phase without phase control (Movie S12 and Fig. S19 in Ref. [27]). For a conventional focused beam [e.g., with focal point

$\mathbf{x}_f = (0, 0, z)$ using 16×16 array at $V_{\text{in}} = 8$ V], this condition is met only for long focal lengths (> 129 mm, a threshold identified numerically in Fig. S14 in Ref. [27]).

We also note a discrepancy between the predicted and observed stability. Numerical calculations predict the transverse stiffness of the Bessel beam comparable to that of a focused beam (Figs. 1, S3, S14, and S15 in Ref. [27]), our experiments reveal higher stability for the Bessel beam. The significance of other possible forces was explored. The lift force from acoustic streaming is negligible ($\sim 10^{-9}$ N, see details in Ref. [27]), and the stable trapping of nonspherical, nonrotating particles indicates that symmetry-dependent or rotation-induced forces such as the Magnus effect, are not the primary source of the observed stability (Movies S3, S4, and S11 in Ref. [27]). Further, our analysis shows that, unlike a focused beam, the Bessel beam sustains restoring transverse radiation force, well above its axial equilibrium point, indicating a larger levitation-capable region in the axial direction (Fig. S14 in Ref. [27]). Yet the physical mechanism responsible for this enhanced stability remains an open question and may involve factors not captured by our model.

Moreover, the numerical model predicts the existence of a single axial equilibrium point [Fig. 1(e)]. However, we observed particles fluctuating between multiple discrete levitation heights in experiments (Fig. S10 in Ref. [27]). The spacing between these heights is approximately half a wavelength $[(\lambda/2) = 4.26 \text{ mm}]$. Our pressure field measurements (Fig. S5 in Ref. [27]) confirm that the constructed field retains the characteristics of a traveling wave and matches numerical simulations, thereby ruling out the formation of zero-pressure nodes. Interestingly, a simple model including a weak reflection from the ceiling of only 6 Pa ($< 1\%$ of the incident beam), corresponding to the PAT being positioned ~ 1.55 m (182λ) from the ceiling (Fig. S16 in Ref. [27]), qualitatively reproduces the emergence of the discrete levitation heights (albeit a more complete reflection model is necessary to fully evaluate the effect of reflections on trap stability). This finding demonstrates that accounting for reflections, even when their amplitudes are multiple orders of magnitude smaller than the incident wave, is essential for the future design of single-sided levitation systems. Indeed, both additional experiments in a high-ceiling facility (6.22 m) and corresponding numerical simulations confirm that these fluctuations persist even when the reflected pressure is minimized to ~ 1.6 Pa (see Movie S13 and Fig. S17 in Ref. [27]). Furthermore, the observed vertical fluctuations are attributed to temporal variations in the acoustic pressure amplitude (Fig. S18 in Ref. [27]), which induce corresponding axial perturbations in both the acoustic radiation force and acoustic streaming.

These results establish a novel mode of acoustic levitation, distinct from previous methods based on entrapping particles between high-pressure regions, such as at the

nodes of a standing wave or in the central minima of twin and vortex traps. The unique advantages of this high-pressure trapping, including its robustness against obstacles and longer working distance, establish a new platform for versatile noncontact manipulation in an open environment.

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Data availability—The data that support the findings of this Letter are openly available [60].

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End Matter

Analytical expression for transverse restoring force— Following Fan and Zhang [17,26], we explain the analytical condition under which a zero-order Bessel beam generates a transverse restoring force. When the scattering force is negligible, the time-averaged acoustic radiation force on a compressible sphere of radius a in the Rayleigh regime can be expressed as $\mathbf{F} = -\nabla U$, where the Gor'kov potential [12,37] is given by

$$U = V_p \left(\frac{1}{2} \kappa_0 f_1 \langle p^2 \rangle - \frac{3}{4} \rho_0 f_2 \langle \mathbf{v}^2 \rangle \right), \quad (\text{A1})$$

where $V_p = (4/3)\pi a^3$ is the particle volume, κ_0 is the compressibility of the medium, ρ_0 is the medium density, $\mathbf{v}$ is the particle velocity, and $\langle \cdot \rangle$ denotes a time average. The monopole and dipole coefficients are defined as $f_1 = 1 - (\kappa_p/\kappa_0)$ and $f_2 = [2(\rho_p - \rho_0)/(2\rho_p + \rho_0)]$, where κ_p and ρ_p are the compressibility and density of the particle, respectively. The first term represents the monopole (pressure-gradient) contribution and the second the dipole (velocity-gradient) contribution. Substituting the sound pressure field of a zero-order Bessel beam [Eq. (1)] and the corresponding particle velocity $\mathbf{v} = (1/j\omega\rho_0)\nabla p$ into Eq. (A1) yields

$$U = \frac{1}{8} \kappa_0 P_A^2 V_p [(2f_1 - 3f_2 \cos^2 \beta) J_0^2 - 3f_2 \sin^2 \beta J_1^2], \quad (\text{A2})$$

where the argument $(kr \sin \beta)$ of the Bessel functions is omitted for brevity. The transverse radiation force is then obtained as $F_r = -(\partial U / \partial r)$, and the lateral stiffness at the beam axis ($r = 0$) is evaluated using small-argument approximations for the Bessel functions, giving

$$\begin{aligned} -\frac{\partial F_r}{\partial r} \Big|_{r=0} &= \frac{\partial^2 U}{\partial r^2} \Big|_{r=0} \\ &= \frac{(k \sin \beta)^2}{16} \kappa_0 P_A^2 V_p [-4f_1 + (9\cos^2 \beta - 3)f_2]. \end{aligned} \quad (\text{A3})$$

A positive value of Eq. (A3) indicates a restoring force toward the beam axis. The sign is determined by the balance between the pressure-gradient (f_1) term and the velocity-gradient (f_2) term:

$$-4f_1 + (9\cos^2 \beta - 3)f_2 > 0. \quad (\text{A4})$$

This condition defines a critical cone angle for a zero-order Bessel beam [17,26], with $f_2 > 0$ (i.e., $\rho_p > \rho_0$):

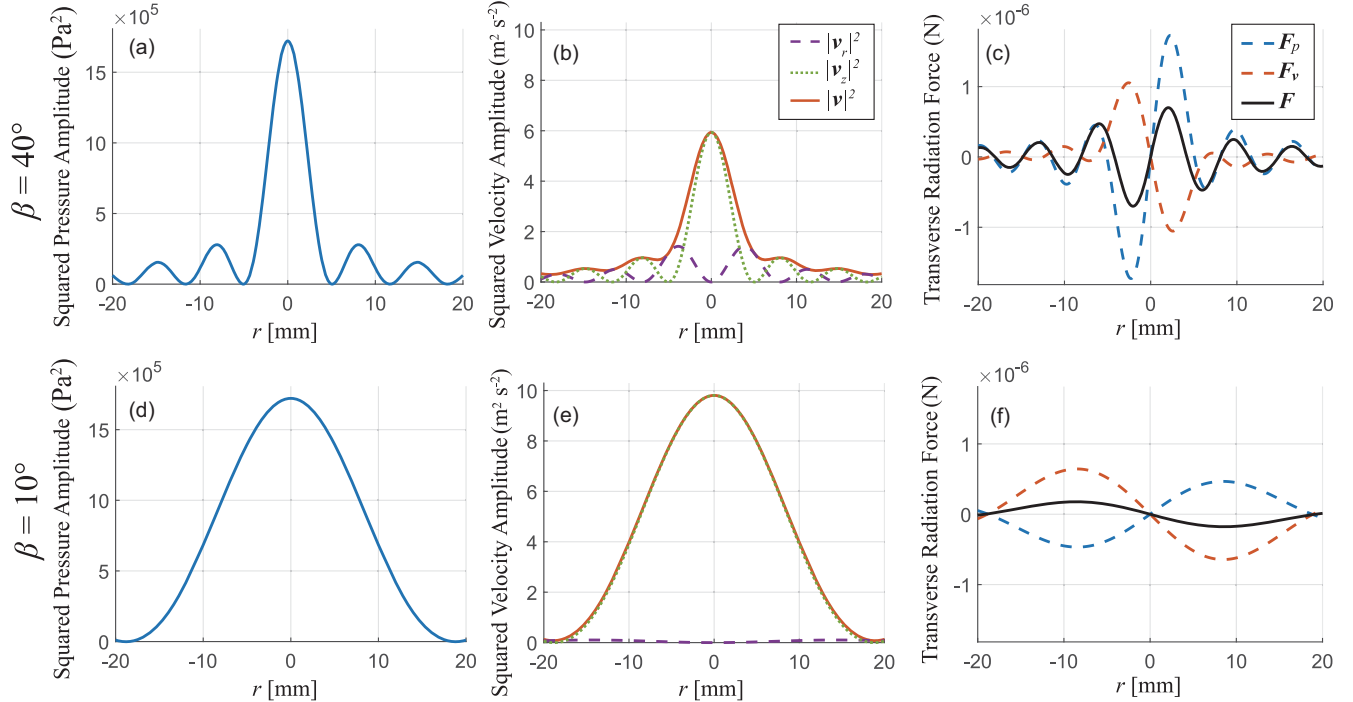
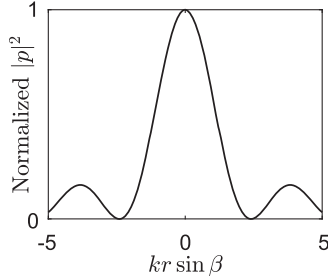
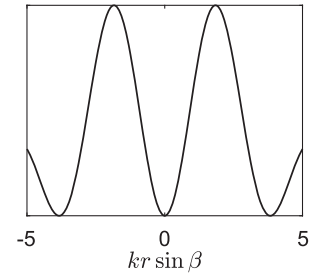


FIG. 5. Decomposition of the transverse radiation force on an EPS sphere ($a = 0.75$ mm) for an ideal zero-order Bessel beam with $P_A = 1312$ Pa, the on-axis maximum in Fig. 1(d). (a)–(c) $\beta = 40^\circ$ and (d)–(f) $\beta = 10^\circ$: squared pressure amplitude (a), (d), squared velocity amplitude components [(b),(e); total $|\mathbf{v}|^2$, radial $|v_r|^2$, axial $|v_z|^2$], and transverse radiation force (c),(f) decomposed into the pressure-gradient term F_p , velocity-gradient term F_v , and their sum F . Panel (c) shows that the pressure-gradient term dominates and the net force is repulsive ($\beta > \beta_c$); panel (f) shows that the velocity-gradient term dominates and the net force is restoring ($\beta < \beta_c$).

TABLE I. Transverse trapping conditions for zero-order and first-order Bessel beams in the Rayleigh regime. The cone-angle conditions follow from the Gor'kov potential [17,26]. Values in parentheses are for an EPS sphere in air ($a = 0.75$ mm, $f_1 = 0.996$, $f_2 = 0.956$).

	Zero-order Bessel beam	First-order Bessel (vortex) beam
Pressure profile		
Trapping location	Pressure antinode	Pressure node
Cone-angle condition	$\beta < \cos^{-1} \sqrt{(4f_1 + 3f_2)/9f_2}$ (26.8°)	$\beta > \sin^{-1} \sqrt{(3f_2 - 2f_1)/6f_2}$ (23.0°)

$$\beta < \beta_c = \cos^{-1} \sqrt{\frac{4f_1 + 3f_2}{9f_2}}. \quad (\text{A5})$$

For expanded polystyrene in air ($f_1 = 0.996$, $f_2 = 0.956$), $\beta_c = 26.8^\circ$. Since both the nominal cone angle $\beta = 20^\circ$ and the maximum angle during vertical translation $\beta = 25^\circ$ [Fig. 2(e)] remain below β_c , the lateral radiation force is directed toward the beam axis throughout our experiments. Conversely, for $\beta > \beta_c$ the pressure-gradient term dominates, and the on-axis lateral force becomes repulsive.

To illustrate the role of the cone angle, Fig. 5 compares the pressure and velocity contributions for two representative cases. For a large cone angle ($\beta = 40^\circ$), the repulsive pressure-gradient term F_p outweighs the attractive velocity-gradient term F_v , resulting in a net repulsive force near

the axis [Fig. 5(c)]. For a small cone angle ($\beta = 10^\circ$), the velocity-gradient term dominates, yielding a net restoring force [Fig. 5(f)]. Although the above derivation assumes an ideal Bessel beam with infinite aperture, a restoring transverse radiation force persists for the finite-aperture beam generated by the PAT, as confirmed numerically in Fig. 1(c).

The counterpart for trapping at a pressure node is a first-order (vortex) Bessel beam, for which an analogous calculation yields the cone-angle condition listed in Table I. A Bessel beam generated by a finite aperture of radius R maintains its beam structure only up to $z_{\max} = (R/\tan\beta)$ [21]. Hence, because the first-order Bessel beam requires $\beta > 23.0^\circ$ for transverse trapping, the finite aperture imposes a range limit $z_{\max}$ on this type of trapping. For a zero-order beam, by contrast, β can in principle be made arbitrarily small, extending $z_{\max}$ correspondingly.