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ABSTRACT

We introduce a hologram-based method to determine the physically optimal axis for measuring the orbital angular momentum (OAM) transferred by acoustic vortex beams to an absorbing target. The axis is aligned with the net radiation force vector obtained from holographically measured pressure field. This alignment eliminates the transverse force component, making the measured torque independent of lateral position and equal to the OAM flux. The method is validated with vortex beams generated by multi-sector phase plates on a planar transducer and significantly improves upon conventional geometric alignment for nonparaxial and aberrated beams.

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Structured waves carrying orbital angular momentum (OAM) have been intensively studied since the seminal work of Allen *et al.*,[1] who showed that Laguerre–Gaussian laser modes with azimuthal index l carry orbital angular momentum $l\hbar$ per photon, separate from spin angular momentum. This discovery introduced a new degree of freedom in wave physics and led to numerous applications in optical manipulation, communications, and quantum optics.[2,3]

In acoustics, vortex beams demonstrate analogous potential for contactless rotation and acoustic tweezers.[4–6] Quantitative measurement of acoustic OAM transfer is usually performed using torsional pendulums or balances. In nearly all such experiments, the rotation axis of the pendulum is aligned with the "beam axis" using geometric criteria: the intensity centroid, the center of the dark core, or the apparent position of the phase singularity.[7–10] Although this approach works for clean paraxial beams, it becomes fundamentally problematic for real experimental beams that may be misaligned, aberrated, asymmetric, or nonparaxial. In these cases, the measured torque contains an uncontrolled extrinsic OAM contribution caused by transverse linear momentum.[11,12] Previous works have addressed this problem mainly through increasingly careful geometric alignment.

Here, we introduce a radiation-force alignment method that solves this long-standing issue rigorously. The measurement axis is aligned with the net radiation force vector computed from the holographically measured pressure field in a plane corresponding to the position of an absorbing surface. This alignment nullifies the transverse force component, making the measured torque independent of lateral position and equal to the full orbital angular momentum flux (i.e., the OAM passing through the transverse cross section per unit time) along the actual momentum flux direction.

Consider a harmonic acoustic wave with cyclic frequency ω, characterized by complex amplitudes of acoustic pressure p and particle velocity $\mathbf{v}$. Within the second-order approximation, the acoustic radiation force acting on a volume surrounded by a surface is expressed in terms of first-order quantities only.[13] For harmonic waves, the surface radiation force density is[14]

$$\mathbf{f} = \left(\frac{\rho|\mathbf{v}|^2}{4} - \frac{|p|^2}{4\rho c^2}\right)\mathbf{n} - \frac{\rho}{2}\mathrm{Re}\left[\mathbf{v}^*(\mathbf{v}\cdot\mathbf{n})\right], \tag{1}$$

where ρ and c are the density and speed of sound in the medium, respectively, and $\mathbf{n}$ is the external unit normal. For an ideal absorber lying in the plane $z = 0$ with transverse size larger than the beam diameter, the total radiation force is

$$\mathbf{F} = \iint dxdy\, \mathbf{f}(x, y, 0), \tag{2}$$

and the torque about the z axis is

$$M_z = \iint dxdy\left(xf_y - yf_x\right). \tag{3}$$

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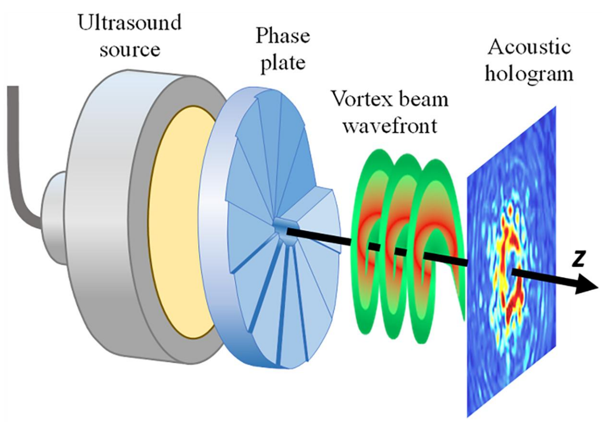

FIG. 1. (single column). Experimental setup for generating and characterizing an acoustic vortex beam. A 100 mm-diameter planar piezoelectric transducer operating at 1.12 MHz emits an ultrasound beam in water, which is transformed into a vortex beam by a 12-sector acrylic phase plate with stepwise thickness variation. The complex pressure field (magnitude and phase) is measured in a transverse plane using a miniature hydrophone to form the acoustic hologram used for subsequent radiation force and OAM calculations.

The radiation force is invariant under transverse beam shifts, while the torque depends on the relative position of the beam and rotation axes. Shifting the rotation axis from the origin $(0,\ 0)$ to the point $(x_0\,, y_0)$ changes the torque as

$$M_z(x_0\,, y_0) = M_z(0,\ 0) - x_0 F_y + y_0 F_x. \tag{4}$$

This dependence creates the fundamental problem: the measured torque cannot be uniquely determined. The uncertainty arises from the nonzero transverse force component $\mathbf{F}_\perp = (F_x,\ F_y,\ 0)$. The problem is eliminated when the beam axis is chosen along the total radiation force direction, i.e., $\mathbf{m} = \mathbf{F}/|\mathbf{F}|$.

The proposed solution is based on acoustic holography.[15] The complex amplitude of the acoustic pressure $p(x, y, 0)$ is measured on a dense grid, forming the hologram. Its angular spectrum $S(k_x,\ k_y)$ is calculated, from which the full pressure and velocity fields are obtained. The total force $\mathbf{F}$ is computed using Eqs. (1) and (2). A new coordinate system with the z' axis along $\mathbf{m}$ is introduced using the rotation matrix constructed from the orthonormal basis $\mathbf{e}'_z = \mathbf{m}$, $\mathbf{e}'_x = \mathbf{e}_y \times \mathbf{m}/|\mathbf{e}_y \times \mathbf{m}|$, and $\mathbf{e}'_y = \mathbf{e}'_z \times \mathbf{e}'_x$. The angular spectrum is transformed to the new coordinates, and the fields are reconstructed on the plane perpendicular to $\mathbf{m}$. On this plane, the transverse force vanishes by construction, and the torque M_0 about the z' axis is independent of lateral position and equals the full OAM transferred by the beam per unit time. The corresponding line in the original laboratory plane along which a vertical torsional pendulum measures exactly this intrinsic torque M_0 is given by

$$F_y x - F_x y = M_z(0,\ 0) - M_0. \tag{5}$$

In experiment, a planar piezoelectric transducer of diameter 100 mm operating at 1.12 MHz was used. A 12-sector acrylic phase plate with stepwise thickness was attached directly to the radiating surface to impose an azimuthal phase shift of $2\pi l$ for topological charge $l = 1$, following the approach of Terzi *et al.*[16] The complex pressure field was measured with a miniature hydrophone (HGL-0200, Onda) on a 241×241 square grid with 0.5 mm step at a distance of 58 mm from the transducer, forming the acoustic hologram. From the hologram, the angular spectra of pressure and velocity were computed, the total force vector $\mathbf{F}$ was determined, and the field was transformed to the force-aligned coordinate system using the procedure described above. Note that acoustic holography provides very accurate (within several percent) measurements of the true acoustic field structure when recommended practices regarding step size, scan region dimensions, and temperature stability are followed.[15] For determining the force direction, hydrophone sensitivity does not play a role, eliminating the dominant source of uncertainty in absolute pressure measurements.

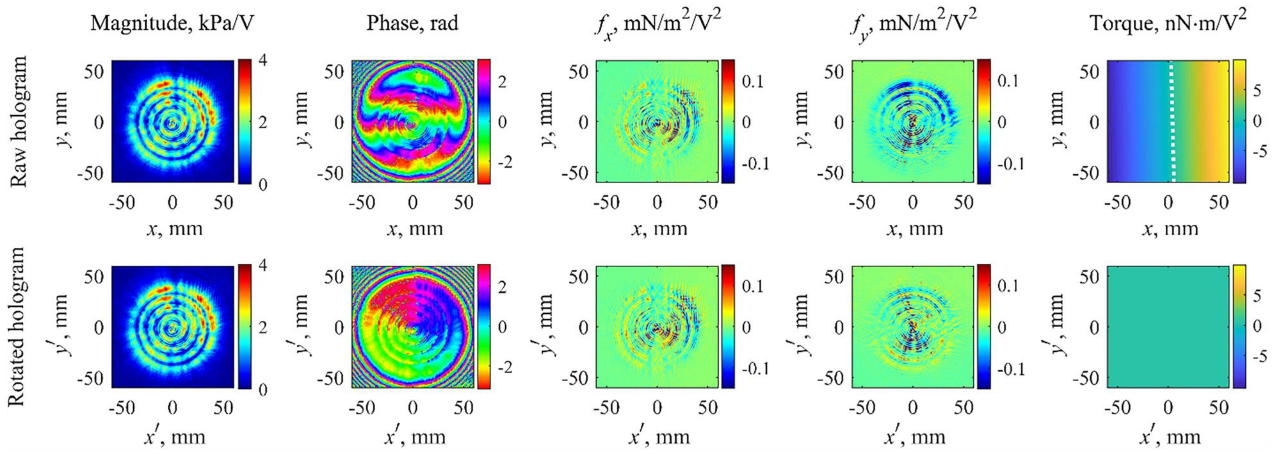

FIG. 2. (double column). Magnitude and phase of the acoustic pressure field, together with the associated distributions of the transverse radiation force components per unit area and the radiation torque in the transverse plane. The pressure amplitude is normalized to the driving voltage amplitude. The radiation force components and torque are normalized to the square of the driving voltage amplitude. Upper row: results in the original coordinate system aligned with the nominal beam axis. Lower row: results after the alignment of the coordinate system with the total radiation force vector. The dotted line on the upper torque map shows the line of action of the transverse radiation force. When the rotation axis intersects this line, the measured torque equals the orbital angular momentum transferred by the beam per unit time.

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Figure 1 shows the experimental setup. Figure 2 presents the magnitude and phase of the acoustic pressure field together with the distributions of transverse radiation force components per unit area and radiation torque. In the original coordinate system, the torque varies strongly with position within the range −8.7 to +8.2 nN m/V^2 and even changes sign. The corresponding force components were $F_x = 3.91 \times 10^{-9}$ N/V^2, $F_y = -1.66 \times 10^{-7}$ N/V^2, and $F_z = 4.43 \times 10^{-6}$ N/V^2, corresponding to force inclination angles $\alpha_x = \arcsin(F_x/|\mathbf{F}|) \approx 0.050°$ and $\alpha_y = \arcsin(F_y/|\mathbf{F}|) \approx -2.14°$. After aligning with the total radiation force vector, the torque distribution becomes uniform (fluctuating from 0.455 87 to 0.455 94 nN m/V^2 within the 100×100 mm^2 region; standard deviation <0.01%), yielding the intrinsic torque $M_0 = 0.456$ nN m/V^2.

The dotted line on the upper torque map indicates the line of action of the transverse radiation force. The intersection of the rotation axis with this line gives the orbital angular momentum transferred by the beam per unit time. Note that the location of this line can be determined independently of hydrophone sensitivity, whereas the absolute torque value requires a calibrated hydrophone. Therefore, when using an uncalibrated hydrophone, the intrinsic torque can be measured directly by positioning the rotation axis on this line.

The proposed algorithm extracts the orbital angular momentum of a vortex beam using only the experimentally measured hologram, without separate measurements of small forces and torques. The method can also be realized alternatively by measuring axial force F_z and torque M_z at different positions (x_0, y_0) and determining the transverse components from the linear dependence in Eq. (4). This allows correction of the transducer orientation to eliminate the transverse force.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Oleg A. Sapozhnikov: Conceptualization (lead); Funding acquisition (lead); Methodology (lead); Project administration (lead); Supervision (lead); Writing – original draft (lead); Writing – review & editing (lead). **Liubov M. Kotelnikova:** Data curation (lead); Formal analysis (lead); Software (lead); Visualization (lead); Writing – review & editing (supporting). **Sergey A. Tsysar:** Investigation (lead); Resources (equal); Validation (lead); Writing – review & editing (supporting).

DATA AVAILABILITY

All data needed to evaluate the conclusions of the paper are present in the paper.

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