

Trapping of a flexible disk in a vortical flow: Reconstruction process, measurements, and theory

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Thin-heavy-flexible disks are observed orbiting at a quasistable radial position from the axis of a strong vortex. Given that the disks are denser than the fluid, it is surprising that they persist in orbit rather than being centrifuged away from the vortex. A 3D reconstruction technique was used to track both the position and deformation of the thin flexible disk, providing insight into the mechanisms underlying the trapping phenomenon. The reconstruction process uses shape-from-silhouette to define an initial 3D reconstruction, which is subsequently refined by minimizing a cost function based on physical and visual criteria. The results of the 3D reconstruction measurements are presented and compared with a phenomenological model. The analysis shows that orbital stability depends on a combination of vortex parameters (strength and core size) and particle parameters (trajectory curvature, surface curvature, angle of inclination, and slip velocity).

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I. INTRODUCTION

One of the key physical processes involved in the dispersion of plastic in the ocean is turbulence-driven vertical mixing [1]. A significant complication in understanding the transport of these environmental plastics stems from the fact that they range in size and density, both lighter and heavier than water, and take on random shapes that can evolve due to deformation.

The influence of particle density on the transport of particles in turbulence has been investigated extensively for the specific case of small spherical particles. Numerous studies on the subject have shown that spherical particles heavier than the fluid tend to be expelled from regions of high vorticity [2]. Furthermore, a strong correlation has been found between regions of high-pressure-gradient magnitude and low concentrations of particles with large Stokes numbers [3]. These findings, grounded in classical dynamics, would lead one to expect that heavy particles in a strong vortex should be centrifuged away from the axis of rotation.

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Although classical findings apply to simple particle geometries, they do not capture the rich behavior that emerges once shape or flexibility variations are introduced. In turbulent or vortical flows, the interplay between particle anisotropy, deformability, and inertia can lead to dynamics that depart markedly from those of spherical particles. To explore how the shape of the particles modifies these dynamics, numerous studies have examined the rotation of rigid fibers and disks in turbulence, as reviewed by Voth and Soldati [4]. Much less work has addressed the transport of particles with increased shape complexity. Complex particle shapes can generate rich dynamics even in the seemingly simple case of settling, as observed for chiral particles [5] and bent disks [6,7], further highlighting how much more there is to explore regarding their transport in turbulence. A first step toward a better understanding of this physical problem is to investigate the dynamics of complex-shaped particles in vortical flows, as turbulence can be seen as an ensemble of vortex filaments interacting with each other.

While the majority of studies investigating inertial particle dynamics in vortical flows have focused on spherical, rigid particles, recent work has begun to examine the effects of particle shape and flexibility. The dynamics of anisotropic particles has been examined by Yerasi *et al.* [8], where the behavior of an inertialess dumbbell within a vortex is investigated. Depending on its initial orientation, position, and the fixed distance between the two spheres, a range of spirographic trajectories has been observed. These observations underscore that finite-size anisotropic particles do not behave as small spherical particles in the vicinity of a vortex.

Deformability can also influence the dynamics of particles in vortical flows, as seen in the work carried out by Fujiki *et al.* [9]. The investigators studied the dynamics of a deformable, neutrally buoyant, spherical particle within a Taylor-Green vortex. In contrast to rigid neutrally buoyant particles, which orbit at a given distance to the vortex, the deformable particles migrate toward the center of the vortex. In particular, this phenomenon has also been observed in 2D turbulence flow, where long, flexible, neutrally buoyant fibers are trapped within the vortex cores more readily than their rigid counterparts [10].

In the continuation of these works, we examine how deformability affects the transport of finite-size particles heavier than the surrounding fluid to determine whether deformability plays a role in counteracting the centrifugal forces responsible for expelling heavy particles. To explore this, we experimentally investigate the behavior of thin-heavy-flexible disks near a vortex. Using 3D reconstruction techniques, we measure the position and shape of the disk during orbit, allowing us to characterize the equilibrium configurations observed in trapping events. We isolate the mechanisms responsible for particle deformation and stable orbiting, providing new insight into how flexibility may allow particles to resist centrifugal expulsion and instead become trapped.

The experimental setup is described first, along with details of the measured flow field and disk characteristics. We then outline the general measurement process, including the 3D reconstruction method and the parameters extracted from the disk's configuration. Experimental results are presented next, followed by a simplified theoretical model that balances centrifugal and pressure forces. The model predictions are compared with the measurements, and the paper concludes with a discussion of the implications and final remarks.

II. EXPERIMENTAL METHODS

A. Setup

The experiments are performed in a 60-cm cubic tank filled with water. The flow can be illuminated or viewed through the acrylic windows on each face of the cube. The flow field in the tank is generated by eight rotors, each mounted with a 17-cm-diameter impeller with six straight blades of 5-mm height. The impellers are positioned at the vertices of the cube and oriented toward its center. The rotation rate Ω_F of each impeller can be set between 5 and 19 Hz independently. In the present study, a single pair of diagonally opposing impellers is actuated to corotate, generating a vortex along one diagonal of the cube.

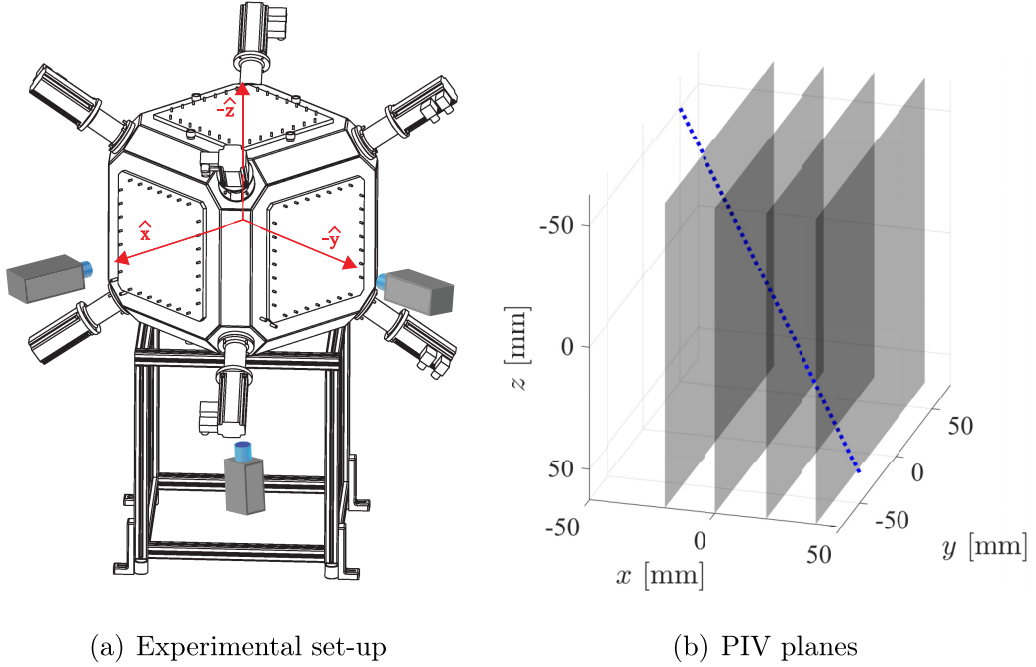


FIG. 1. An illustration of the tank, motors, and position of the cameras is provided in Fig. 1(a). The location of the planes where PIV measurements were taken with respect to the physical center of the tank in the laboratory frame of reference is shown in Fig. 1(b). The blue dotted line [$\cdots$] is provided to indicate the expected position of the vortex center line along the diagonal of the tank.

Video acquisition is carried out by three synchronized high-speed cameras (VEO 710L), each equipped with a ZEISS Milvus 2/100M ZF.2. The images used for the reconstruction were recorded at a sampling rate of 3000 Hz with an exposure of 330 μ s. The cameras are positioned to provide three approximately orthogonal views of the volume of interest. An illustration of the relative positions of the tank, motors, and cameras is provided in Fig. 1(a). Through the windows on the opposite sides of the cameras, the backlighting for the captures is provided by three LED panels. The LED panels are energized by DC power supplies to ensure continuous illumination.

B. Flow characterization: PIV

The flow field of the vortex was characterized for a range of forcing frequencies, Ω_F , using multiplanar PIV measurement. For these measurements, the tank was seeded with polyamide seeding particles of diameter 50 μ m (Dantec Dynamics). The PIV images were captured using a Dantec Flowsense EO camera, and illumination was provided by an Nd:YAG pulsed laser at 532 nm. The investigation was carried out using DynamicStudio for both the capture and PIV data analysis.

Each measurement of a given forcing frequency in a given measurement plane consists of 600 image pairs sampled at 6.29 Hz with 500 μ s between pulses. The images have a pixel resolution of 3399×2712 pixels, with a spatial resolution of 48.5 μ m/pixels. DynamicStudio's Adaptive PIV scheme was used to evaluate the velocity fields. The size of the interrogation window was set in a range between 128 and 64 pixels with a grid step size of 32 pixels in both directions. Figure 1(b) provides an illustration of the laser sheet positions used in the characterization.

As the axis of the vortex is not aligned with any of the viewing planes of the tank, the planes of the PIV measurements are not orthogonal to the axis of the vortex. However, the azimuthal velocity of the vortex can be inferred by adjusting for the difference in alignment between the normal vector

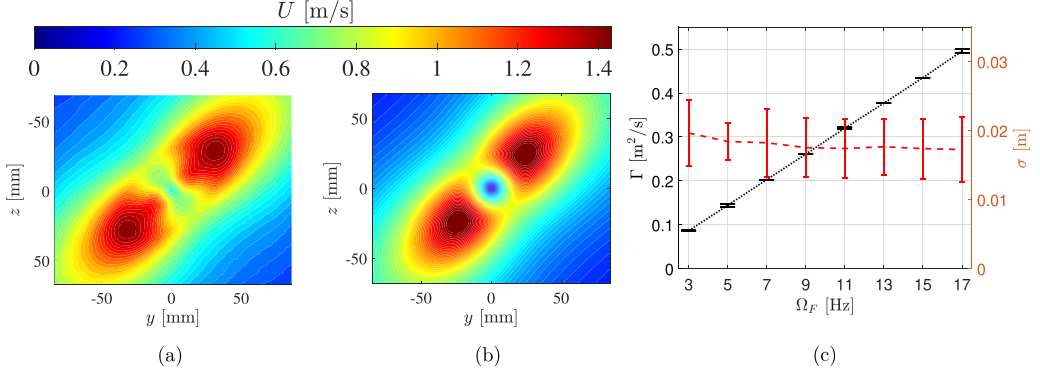


FIG. 2. Figure 2(a) shows the 2D-PIV measurement of the time-averaged velocity magnitude at the center plane ($x = 0$) for $\Omega_F = 9$ Hz. Figure 2(b) shows the velocity magnitude using the fitted Lamb-Oseen vortex model for the corresponding Ω_F and planes of the PIV measurement. The velocity magnitude in Fig. 2(b) is calculated using the projection of the 3D velocity vector from the model onto the corresponding 2D-PIV measurement plane. Figure 2(c) provides the estimated Lamb-Oseen vortex parameters obtained by averaging across the four measurement planes, with bar half-length representing the standard deviation.

of the measurement plane and the vortex axis. Due to the meandering of the vortex core across image pairs, an averaged value for the velocity field was achieved by a spatial shift in the velocity fields to align the two local velocity magnitude maxima across each respective run [11]. Figure 2(a) shows the measured time-averaged velocity magnitude at forcing frequency $\Omega_F = 9$ Hz from the PIV data. For comparison, Fig. 2(b) presents the velocity magnitude of the fitted Lamb-Oseen vortex model for the same PIV measurement plane and forcing frequency.

Using the results from the vortex frame of reference, the relative difference of the maximum time average velocity magnitude across each measured plane is within 3.4% of the center plane measurement for all forcing frequencies, the strongest of which occurred at 17 Hz for the farthest measurement plane.

The flow in the center of the tank is modeled (to first order) as a Lamb-Oseen. The azimuthal component is given by [12]

$$u_\theta(r) = \frac{\Gamma}{2\pi r} \left(1 - \exp\left(-\frac{r^2}{\sigma^2}\right) \right). \quad (1)$$

The values of circulation, Γ , and the vortex core scale, σ , plotted in Fig. 2(c) are averaged across the measurement planes with the half-length of the bar representing the standard deviation. While the circulation linearly increased with the forcing frequency as expected, the scale of the vortex core decreased to a relatively constant diameter for forcing greater than 9 Hz. Standard deviations are provided to give a sense of the similarity between the flows across the measurement planes at each frequency. The velocity fields, averaged in the vortex frame of reference, were consistent across the multiple planes of measurement, shown in Fig. 1(b), at each forcing frequency. As such, we assume the Lamb-Oseen model to be a fair representation of our flow field within our desired reconstruction volume, a cube of approximately 10 cm in the center of the tank.

C. Flexible disk fabrication

The smooth, flexible disks are made of SFX-10 silicone (Esprit Composite), with a specific gravity of 1.11 and a Young's modulus of $E = 248 \pm 15$ kPa. To make the silicone semitransparent, a small amount of silicone soluble pigment is well mixed into the silicone prior to curing. To form the silicone sheet, the silicone is poured and pulled onto a glass substrate, within a known gap height determining the thickness of the sheet, and allowed to cure. The thicknesses of the sheets used in

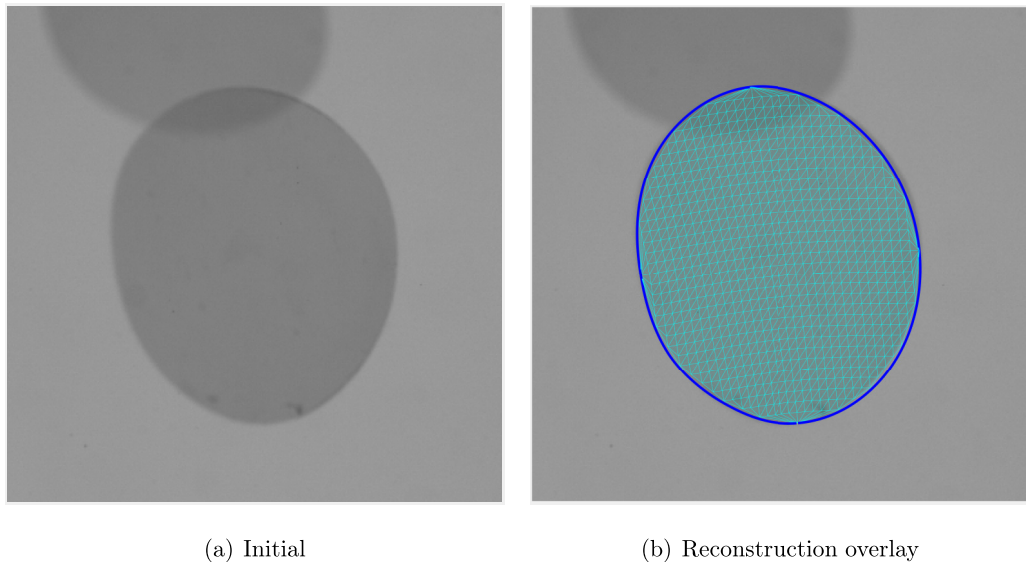


FIG. 3. A sample of a base image, from a single view, is provided in Fig. 3(a) alongside an overlay of the final reconstruction in Fig. 3(b).

this experiment are $h = 352 \pm 13 \text{ } \mu\text{m}$. The roughness of the disk is expected to be on the order of that of the glass substrate ($\lesssim 10 \text{ } \mu$) used for molding. The disks are cut from silicone sheets of uniform thickness using hollow punches with inner radii of 8, 10, and 12 mm.

III. PROCESS

Each measurement is taken when a single disk is observed trapped within the measurement volume. This facilitated the reconstruction and trajectory determination of the disk, avoiding the complications associated with multiparticle Lagrangian tracking [13].

A. Surface reconstruction and curvature evaluation

The 3D reconstruction process begins with simultaneous images of a disk from the three orthogonal views. The semitransparent nature of the disk allows the perimeter of the disk to be seen, even in the presence of occlusions. This visibility allows the pixels pertaining to the perimeter to be isolated using a Canny edge detection algorithm. Using shape-from-silhouette techniques, the perimeter pixels of the three views are used to obtain an estimate of the 3D location of the disk's perimeter. To obtain the reconstruction, a thin plate spline (TPS) is used to represent the reconstructed surface of the disk ([14,15]). The TPS is obtained by defining the correspondence between control points from a 2D disk model to their 3D position in space.

The TPS is then optimized using the costs associated with the bending and stretching energy, in conjunction with a cost associated with the quality of the reprojection. In particular, the cost representing the bending energy is

$$be = \kappa_1^2 + \kappa_2^2 + 2p\kappa_1\kappa_2, \quad (2)$$

where $\kappa_{1,2}$ [16] are the local principal curvatures of the surface reconstruction and p is the Poisson's ratio of the material. For silicone, the accepted ratio of $p = 0.5$ is used. An in-depth discussion of the reconstruction technique and the other costs used are presented in [17].

The resulting TPS allows us to reconstruct the surface of the disk, as illustrated in Fig. 3. The reconstruction is then used to evaluate the evolution of the position and shape of the trapped disk. In

what follows, the term 'configuration' will be used to refer to this general combination of position and shape of the disk. The disk trapping events can now be considered with respect to two expected key parameters: the radius of curvature of the disks' trajectories and their surfaces.

The radius of curvature of a disk's surface, r_{surf} , is obtained using the local bending energy of the disk, as in Eq. (2). An overall value for a disk's surface radius of curvature is obtained by averaging the local values of the fit at the mesh points:

$$\kappa_{\text{surf}}^2 = \frac{1}{M} \sum_{k=1}^M [\kappa_1^2 + \kappa_2^2 + \kappa_1 \kappa_2]_{[k]}, \quad (3)$$

where k indexes through the $M = 793$ grid points of the reconstruction. The radius of curvature of the disk's surface is then defined as $r_{\text{surf}} = \kappa_{\text{surf}}^{-1}$.

B. Trajectory reconstruction

A precise, instantaneous determination of the disk to vortex core distance would have required simultaneous measurements of the flow field and the disk's three-dimensional deformation. Such techniques have been successfully applied to measure bubble deformation [18], but were not available in our laboratory at the time.

In the absence of such measurements, a self-consistent method to define the relative position of the disk with respect to the instantaneous vortex center is used. By tracking the disk's material center, the radius of curvature of its trajectory, r_{traj} , is taken as a quasimeasure of the distance to the vortex core. The material center of the disk is defined by the mesh node at the center of the 2D disk model. Trajectories presented here are measured by tracking this node of the reconstruction at each instance in time, $\vec{x}_c = (x_c, y_c, z_c)$.

In each experimental run, a single disk is registered when it is observed orbiting within the reconstruction volume, regardless of whether that same disk later exits and re-enters the volume of reconstruction. Therefore, within a single run, there can be multiple shorter reconstructed trajectories that pertain to a single trapping event. For analysis purposes, trajectories are considered if the disk is reconstructed for a trajectory longer than 128 frames, with gaps between successful reconstructions not exceeding three frames.

Guided by the periodic nature of the disk's motion about its axis of orbit, a number of Fourier modes are used to fit the measured material center of the disk at each instance in time of the trajectory. The three coordinates of each trajectory, $x_c(t)$, $y_c(t)$, $z_c(t)$, are independently fitted, $\mathcal{P} = (\mathcal{X}(t), \mathcal{Y}(t), \mathcal{Z}(t))$. The root mean square error of the fitted trajectories ranged from 0.025 and 0.179 mm. This fit is used to calculate the curvature of the trajectory:

$$\kappa_{\text{traj}} = \frac{\sqrt{(\mathcal{Z}''\mathcal{Y}' - \mathcal{Y}''\mathcal{Z}')^2 + (\mathcal{X}''\mathcal{Z}' - \mathcal{Z}''\mathcal{X}')^2 + (\mathcal{Y}''\mathcal{X}' - \mathcal{X}''\mathcal{Y}')^2}}{(\mathcal{X}'^2 + \mathcal{Y}'^2 + \mathcal{Z}'^2)^{3/2}}, \quad (4)$$

where $(\cdot)' = \partial(\cdot)/\partial t$ and $(\cdot)'' = \partial^2(\cdot)/\partial t^2$. The instantaneous radius of curvature of the trajectory is then defined as $r_{\text{traj}} = \kappa_{\text{traj}}^{-1}$.

Figure 4(a) shows the normalized motion of the disk's material center in each Cartesian direction, centered on its mean and scaled by the disk radius R . The periodic variations confirm the orbital nature of the motion. Figure 4(b) presents the corresponding evolution of r_{traj} , r_{surf} , and α , over one normalized orbital period. The smoothness observed in the estimate of r_{traj} results from its calculation as a derived value from the fitted 3D particle trajectory. The relatively small changes observed indicate that the disk configuration remains quasisteady. The observed stable orbit and nearly constant inclination angles strongly suggest that the disk configuration results from some equilibrium between the pressure forces exerted by the vortex and the centrifugal forces acting on the particle, as discussed in Sec. V.

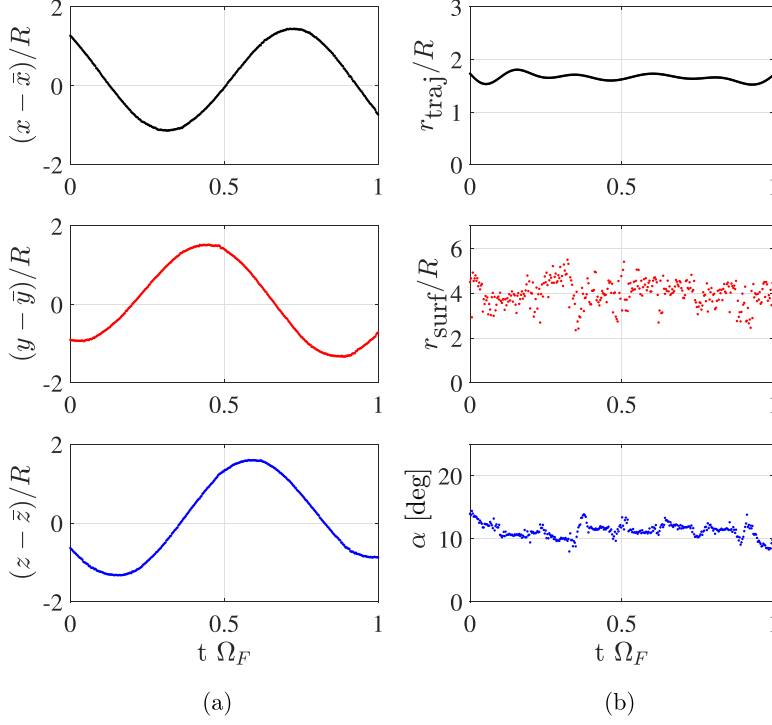


FIG. 4. Measurement of a representative disk with $R = 12$ mm and $\Omega_F = 9$ Hz. Time is normalized by the forcing frequency, $t \Omega_F$, such that one cycle corresponds approximately to one vortex orbit. Figure 4(a) shows a disk's motion in each Cartesian direction, plotted relative to its time-averaged center, normalized by R . Figure 4(b) shows the corresponding evolution of r_{traj}/R , r_{surf}/R , and α .

C. Velocity and orientation definition

Two other parameters observed to play a role in determining the equilibrium configuration are the slip velocity and the angle of inclination of the disk. These will be discussed further in Sec. V.

The velocity of the disk was calculated as the time derivative of its fitted trajectory,

$$\vec{v} = (\mathcal{X}', \mathcal{Y}', \mathcal{Z}'). \quad (5)$$

To quantify the general orientation of the reconstructed disk, the moment of inertia tensor of the disk is calculated:

$$\mathbb{J}_{ij} = \sum_{k=1}^M [m(|\vec{x}|^2 \delta_{ij} - x_i x_j)]_{[k]}, \quad (6)$$

where m is the constant mass assigned to each mesh point.

The apparent angle of inclination, α , is calculated between the velocity vector, $\vec{v}$, and the eigenvector $\hat{e}_3$ of $\mathbb{J}$. For a flat disk, $\hat{e}_3$ corresponds to the axis of symmetry and is oriented radially away from the axis of rotation inferred by the disk's trajectory:

$$\alpha = \sin^{-1}(\hat{v} \cdot \hat{e}_3), \quad (7)$$

where $\hat{v} = \vec{v}/|\vec{v}|$ and $\hat{v} \cdot \hat{e}_3$ is the vector inner product between $\hat{v}$ and $\hat{e}_3$, as shown in Fig. 6(c). For a circular disk, with a single mode of bending with a constant radius of curvature, $\hat{e}_3$ is analogous to the normal vector of the disk's surface at the material center. The vector $\hat{e}_3$ is useful due to its

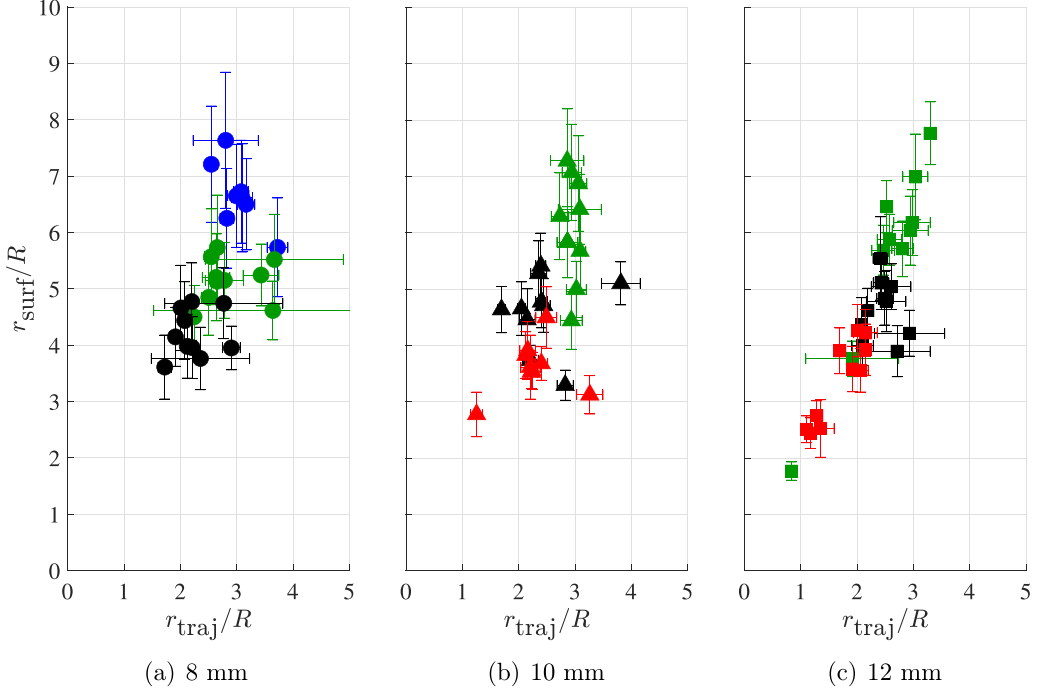


FIG. 5. The mean values over each run, along with corresponding standard deviation bars for disks with radii $R = 8, 10$, and 12 mm, are depicted in Figs. 5(a)–5(c), respectively. The marker colors correspond to the forcing frequency $\Omega_F = 7, 9, 11$, and 13 Hz.

inherently smoother evolution in time, allowing for a clearer tracking than would be possible with a noisier local point measurement.

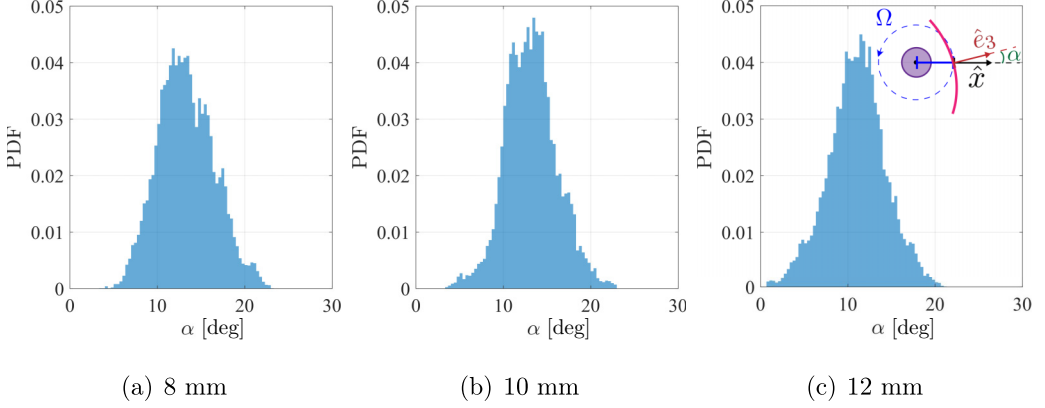
IV. EXPERIMENTAL MEASUREMENTS

For each disk size at each forcing frequency, ten runs have been recorded in which a trapping event was observed. Figure 5 presents the disk's curvature, r_{surf} , as it varies with distance from the vortex core, r_{traj} , for disks of radius $R = 8, 10$, and 12 mm at forcing frequencies $\Omega_F = 7, 9, 11$, and 13 Hz. The values are averaged over each run, with bars indicating the standard deviation.

From the scatter plot in Fig. 5, preferred configurations of r_{traj} and r_{surf} are observed. During trapping events, r_{surf} is greater than r_{traj} . The measurements show that the disk surface does not conform to the local streamlines, remaining relatively flat. All trapping events take place near the vortex core, with certain cases having trajectories within the rotational region of the vortex core, $r_{\text{traj}} < \sigma$.

For the smallest disks, the trapping location and shape are more scattered, whereas for the largest disks, the trend is more pronounced.

From the 3D reconstruction measurements, the angle of inclination, α , between the velocity vector of the disk's center and $\hat{e}_3$ is observed in all trapping events. As shown in Fig. 6, the PDFs of α indicate that the inclination angle is consistently positive, corresponding to an inward tilt relative to the direction of motion around the vortex. For all disk sizes, the distributions are relatively peaked around $\alpha \approx 13^\circ$. Table I reports the ensemble average of the angle of inclination, $\bar{\alpha}$, for each disk's radius and forcing frequency combination tested. During each trapping event, the disk exhibited a consistent inward tilt angle of inclination relative to the direction of motion around the vortex.


 FIG. 6. PDF of measured inclination angle, α , for $R = 8, 10$, and 12 mm and $\Omega_F = 11$ Hz.

V. FORCE MODELING

In this section, a phenomenological modeling of the observations is proposed. The simplest model focuses on two main competing forces acting on the flexible disk: the resultant hydrodynamic pressure force acting across the surface of the disk and the centrifugal force that the disk experiences as it orbits the axis of the vortex. The disk is modeled as having a constant radius of curvature along one direction, as though it were wrapped around a cylinder of radius r_{surf} , with the cylinder's axis of symmetry aligned parallel to the axis of the vortex. It should be noted that the model disk being bent with a constant radius of curvature is a first-order approximation. The curvature along the primary bend would vanish to zero at the edges, as imposed by the boundary conditions, and has been observed in measurements [17]. Here, and in what follows, disk deformation is treated independently of the flow field; perturbations to the base flow and contributions from viscous stresses are neglected.

In this section, the notation used to model the problem is presented, followed by the derivation of the centrifugal and hydrodynamic forces used here.

A. Disk modeling

The notation used in the modeling is defined in the diagram shown in Fig. 7. Here, the disk is illustrated by a cross-sectional view of the disk at vertical position z , $-R \leq z \leq R$. The flexible disk is assumed to orbit at an equilibrium radial position about the vortex center at r_{traj} with a surface radius of curvature, r_{surf} , and with an angular velocity Ω . A cylindrical polar coordinate system is used, where the coordinate system rotates with the angular velocity of the disk, Ω , and the z axis coincides with the vortex axis. In this rotating frame, $\hat{x}$ is the unit vector from the vortex center to

 TABLE I. Average angle of inclination along the standard deviation in degrees, $\bar{\alpha} \pm \sigma_\alpha$, over all reconstructions for a given R and Ω_F .

		Ω_F [Hz]			
		7	9	11	13
R [mm]	8	$14.0^\circ \pm 3.6^\circ$	$15.0^\circ \pm 3.2^\circ$	$13.3^\circ \pm 3.2^\circ$	
	10		$13.5^\circ \pm 2.8^\circ$	$13.2^\circ \pm 3.0^\circ$	$13.5^\circ \pm 3.6^\circ$
	12		$13.5^\circ \pm 4.4^\circ$	$11.0^\circ \pm 3.3^\circ$	$12.3^\circ \pm 4.3^\circ$

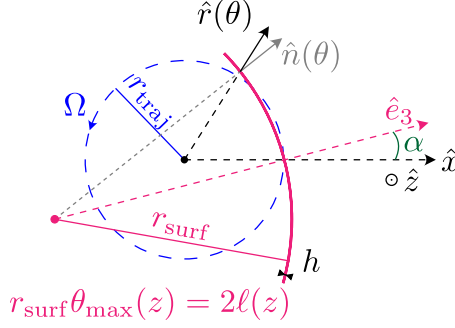


FIG. 7. A cross-sectional view of the disk is provided as a diagram of the model. The disk orbits about the axis of the vortex core at a radius of r_{traj} with a surface radius of curvature, r_{surf} . The disk rotates about the core with an angular velocity, Ω , and an angle of inclination, α . The half-arc length of the disk's cross section in the xy -plane varies as $\ell(z) = R \sqrt{1 - (z/R)^2}$. The radial unit vector and local surface normal along the surface of the disk are used.

the disk's material center. As defined in Eq. (7), the parameter α is the angle of inclination of the disk as it orbits the axis of the vortex.

In the most general configuration, the surface of the disk, $\vec{x}_p$, is constructed in three steps, parametrized by r_{surf} , α , and r_{traj} . First, the surface coordinates of the model disk, $\vec{x}_{p,s}$, bent with a constant radius of curvature, r_{surf} , are

$$x_{p,s}(z) = r_{\text{surf}}(\cos \beta(z) - 1), \quad y_{p,s}(z) = r_{\text{surf}} \sin \beta(z), \quad z_{p,s}(z) = z. \quad (8)$$

Here, $\ell(z) = R \sqrt{1 - (z/R)^2}$ is the half-arc length of a cross section of the xy -plane with a bent disk at $-R \leq z \leq R$ and $\beta(z) = \ell(z)/r_{\text{surf}}$. The bent disk is then rotated about the z axis by an angle of inclination α :

$$\vec{x}_{p,i} = \underline{\underline{R}}(\alpha) \vec{x}_{p,s} = \begin{bmatrix} \cos \alpha & -\sin \alpha & 0 \\ \sin \alpha & \cos \alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_{p,s} \\ y_{p,s} \\ z_{p,s} \end{bmatrix}. \quad (9)$$

Finally, the inclined curved disk is positioned to the radial position of its orbit, r_{traj} , by a translation in the $\hat{x}$ -direction:

$$\vec{x}_p = r_{\text{traj}} \hat{x} + \vec{x}_{p,i}. \quad (10)$$

B. Centrifugal force

The disk rotates with an angular velocity,

$$\Omega = \frac{v_\theta}{r_{\text{traj}}}, \quad (11)$$

where v_θ is the azimuthal velocity of the disk. If the disk follows the flow field exactly, the slip velocity,

$$\Delta u = v_\theta - u_\theta(r_{\text{traj}}), \quad (12)$$

vanishes, so that $v_\theta = u_\theta(r_{\text{traj}})$. In this subsection, we consider this idealized case. The influence of a finite slip velocity, corresponding to the actual azimuthal motion of the disk, will be addressed in Sec. VD. As calculations are performed in a rotating frame at angular velocity Ω , the disk experiences a centrifugal force applied on its center of mass. The centrifugal force experienced

by the disk can therefore be written as

$$|f_c| = \rho_p V_p \frac{u_\theta^2(r_{\text{traj}})}{r_{\text{traj}}^2} r_{\text{cg}} \cos(\alpha), \quad (13)$$

where ρ_p , V_p , and r_{cg} are the density, volume, and center of mass of the disk, respectively. When the disk is inclined, the vector $\hat{e}_3$ and $\hat{x}$ are no longer collinear, as illustrated in Fig. 7. The centrifugal term is therefore multiplied by $\cos \alpha$ to project the force onto $\hat{x}$. The disk's center of mass, r_{cg} , can be written as

$$\tilde{r}_{\text{cg}}(z) = \frac{1}{\ell(z)} \int_0^{\beta(z)} r_{\text{surf}}^2 \cos \theta \, d\theta, \quad (14)$$

$$r_{\text{cg}} = (r_{\text{traj}} - r_{\text{surf}}) + \frac{1}{\pi R^2} \int_0^R \tilde{r}_{\text{cg}}(z) \ell(z) \, dz, \quad (15)$$

where $\ell(z) = R \sqrt{1 - (z/R)^2}$ is the half-arc length of a cross section of the xy -plane with a bend disk at $-R \leq z \leq R$ and $\beta(z) = \ell(z)/r_{\text{surf}}$ is the associated angle the arc makes with the origin.

To assess whether the disk, with respect to the axis of the vortex, will be drawn inward, expelled outward, or remain at the same radial position, only the radial component of the forces is considered. In the reference frame rotating with the disk, this corresponds to the $\hat{x}$ direction.

C. Hydrodynamic force

As shown in Sec. II B, the laboratory velocity field is well described by a Lamb-Oseen vortex. The velocity field in the laboratory reference frame is only in the $\hat{e}_\theta$ direction, invariant in $\hat{e}_z$, and varies only as a function of the radial distance from the center of the vortex. In this case, the pressure gradient in the radial direction is

$$\frac{\partial P}{\partial r} = \rho_f \frac{u_\theta^2(r)}{r}, \quad (16)$$

where ρ_f is the density of the fluid. The pressure force acting on the disk is proportional to the pressure difference across the two faces of the disk. As the pressure gradient is strictly positive, this force is radially inward. Across the thickness of the thin disk ($h \ll R$), the pressure difference can be approximated by

$$\Delta P = \hat{n} \cdot \hat{r} \frac{\partial P}{\partial r} h (1 + \mathcal{O}(h/r)), \quad (17)$$

where $(\hat{n} \cdot \hat{r})$ projects the radial pressure gradient onto the surface normal, accounting for the misalignment between the two directions.

For a small surface element $dA = dz \, r_{\text{surf}} \, d\theta$ at $\vec{x}_p$, the radial distance from the axis of the vortex is $r = \sqrt{x_p^2 + y_p^2}$ and the surface normal of the element is denoted as $\hat{n}$. As the pressure gradient acts in the radial direction with respect to the center of the vortex, the magnitude of the force acting on a surface element is calculated as

$$|f_h| = \int_S h (\hat{n} \cdot \hat{r}) \frac{\partial P}{\partial r}(\vec{x}_p) (\hat{n} \, dA \cdot \hat{x}), \quad (18)$$

where $\hat{r} = \vec{x}_p/|\vec{x}_p|$. The integral is evaluated numerically by integrating the contributions of surface strips at each z across the disk. To calculate the total radial component of the force that the disk will experience, only the contributions in $\hat{x}$ are considered.

D. Viscous force

To justify neglecting viscous effects, we estimate the ratio of the pressure force across the disk to the viscous force arising from its interaction with the flow. This dimensionless ratio serves as a

Reynolds number characterizing the strength of the flow modification by the disk. The viscous force due to flow perturbation is expected to scale as

$$F_v \sim 2\mu R \Delta u_s, \quad (19)$$

where μ is the dynamic viscosity and the slip velocity, between the disk and the local fluid, is defined as

$$\Delta u_s = v_p - u_\theta. \quad (20)$$

The small fractional deviation from the azimuthal velocity is defined as

$$\delta = \Delta u_s / u_\theta. \quad (21)$$

In the measurements, the disk follows a curved path while orbiting the vortex, with only a small portion of its velocity directed along the axis of the vortex. As such, the particle's azimuthal velocity is approximated by the total magnitude of its measured velocity, $v_p \approx |\vec{v}|$. The pressure force can be estimated from Eq. (16) and scales as

$$F_p \sim \pi R^2 \cdot \frac{\rho u_\theta^2}{r_{\text{traj}}} \cdot h. \quad (22)$$

By comparing the ratio of pressure to viscous force,

$$Re = \frac{F_p}{F_v} = \frac{\pi h R \rho u_\theta}{2\mu r_{\text{traj}}} \cdot \frac{u_\theta}{\delta \cdot u_\theta}. \quad (23)$$

Using $\nu = \mu/\rho$ and substituting $u_\theta \sim r_{\text{traj}}\Omega$, we simplify

$$Re \sim \frac{\pi h R \Omega}{2\delta \nu}. \quad (24)$$

Comparison between the measured values of v_p and the expected local velocity of the Lamb-Oseen model gives an estimated slip magnitude of $\mathcal{O}(\delta) = 10^{-2}$. Using values representative of the experimental conditions gives $Re \sim 10^3$, indicating that pressure forces on the disk greatly exceed viscous forces arising from flow perturbations.

VI. INFLUENCE OF KEY PARAMETERS

We observed experimentally that the trapped disks adopt a bent shape with an inclination angle α and rotate consistently slower than the fluid at the disk center. This section considers how the three parameters influence the orbital position of the disk. As shown in Eq. (18), the first two parameters predominantly affect the resulting pressure force, which varies with the disk's position and geometry. In contrast, the centrifugal force is primarily modified by the slip velocity, Δu_s , as the model is derived in the rotating frame about the vortex axis at the disk's orbital frequency.

To step through the impact of each parameter on the model, we will first investigate the reference case $\alpha = 0$ and $\Delta u_s = 0$. The influence of the angle of inclination is then considered, followed by our approach to address the slip velocity.

A. Base model: Axisymmetric orbit

To begin, a stripped-down model is considered, where the flexible disk is assumed to take on the same equilibrium radial position about the vortex center, r_{traj} , and the surface radius of the curvature, r_{surf} . The disk is assumed to conform to the circular streamline of the equilibrium radial position about the vortex center, $\alpha = 0^\circ$, and move with the fluid flow, $\Omega = u_\theta(r_{\text{traj}})/r_{\text{traj}}$.

A normalized force difference,

$$\mathcal{F} = (|f_c| - |f_h|)/(\rho_f \Gamma^2), \quad (25)$$

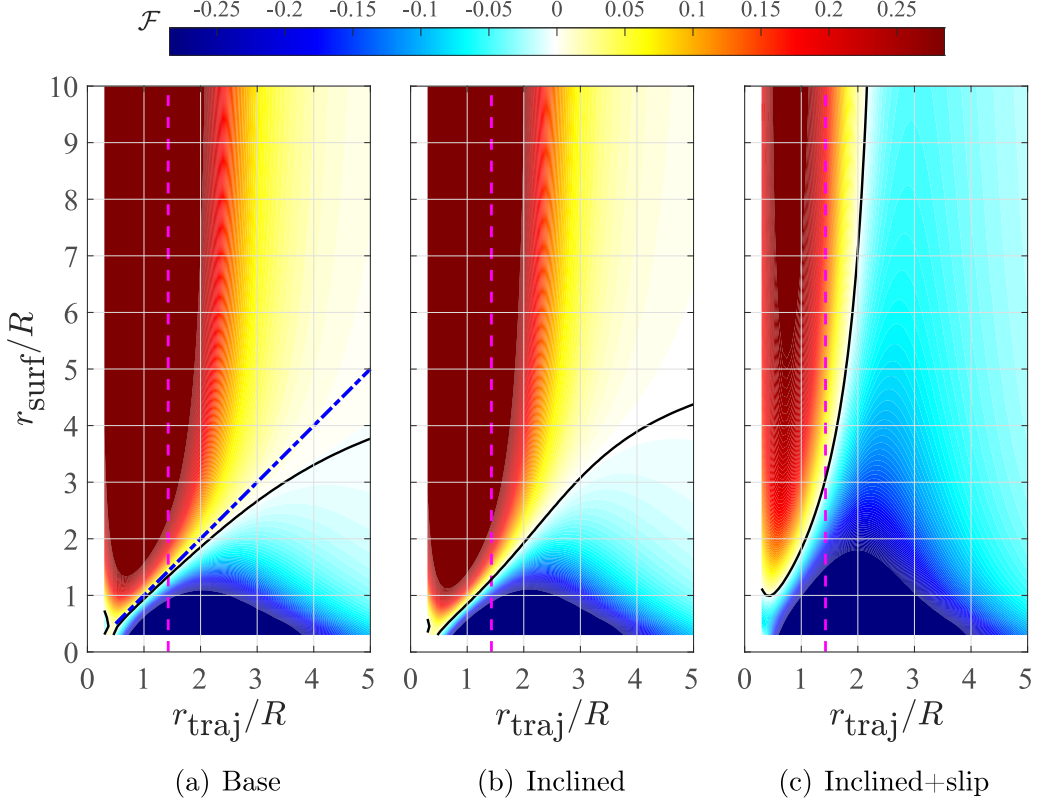


FIG. 8. The normalized net force, $\mathcal{F}$, with respect to r_{traj} and r_{surf} for a disk of $R = 12$ mm with flow parameters corresponding to $\Omega_F = 11$ Hz are presented for the three models considered, together with the simplest subcase. The $\text{---}\text{---}\text{---}$ traces the model solution corresponding to $r_{\text{traj}} = r_{\text{surf}}$. The dashed magenta line $\text{---}\text{---}$ corresponds to the core size $\sigma(\Omega_F)/R$, and the black contour line --- traces where the net force vanishes to zero. Figure 8(a) shows the results based on the assumption of the base model. Figure 8(b) introduces an angle of inclination $\alpha = 12.3^\circ$. Figure 8(c) shows the results of the model assuming a constant small slip velocity between the disk and the fluid's velocity of $\delta = -2\%$.

is used to compare the magnitude of the centrifugal and hydrodynamic pressure force on the particle for all models. As expected, in the case where $r_{\text{traj}} = r_{\text{surf}}$, traced by a blue dashed-dotted line in Fig. 8(a), the centrifugal forces always dominate. Regardless of whichever radial position the disk takes, the disk would always drift radially away under these parameters.

One modification of this base model is to allow the radius of curvature of the trajectory, r_{traj} , and of the surface, r_{surf} , to vary independently of one another while maintaining an orientation of the disk where the normal at the center of the disk remains parallel to $\hat{x}$. By varying both the radii of curvature and numerically evaluating the integrals, a force balance space is obtained, Fig. 8(a). In the red regions, centrifugal forces dominate, pushing the disk outward and away from the vortex core, while in the blue regions, hydrodynamic pressure forces dominate, pulling the disk inward. Between these extremes lies a curved band of near-zero net force, where the disk can maintain an equilibrium orbit, indicated by a black contour line.

The equilibrium position is stable because, for a given surface curvature, a small perturbation of the disk's position, inward or outward, leads to an increase in net force, causing the disk to return to its initial location. However, stability with respect to perturbations in the disk's curvature cannot be captured by our model, as this would require accounting for the restoring elastic forces, which

are not included here. Although the model predicts the existence of an equilibrium position, it does not accurately reproduce the measurements. In particular, the model predicts that the disk's surface radius of curvature is smaller than the trajectory radius, in contradiction to the observations shown in Fig. 5(c).

However, the agreement between the experimental measurements, Fig. 5(c), and the model predictions, Fig. 8(a), remain limited.

B. Inclined model: Orbit with fixed incline

Measured observations, as seen in Fig. 6, suggest that the assumption $\hat{e}_3 \cdot \hat{x} = 1$ in the model should be reconsidered. As shown in Fig. 8(b), the diagram of the total force balance when modeling the disk with an angle of inclination, $\alpha = 12.3^\circ$, corresponds to the mean value of the angle of inclination at 11 Hz. A shift in the parameter space is observed when compared to the results in Fig. 8(a), where $\alpha = 0^\circ$.

The band of vanishing net force of this model is in better agreement with the measurements. The break in symmetry of forces about the center of the disk, due to the inclination, allows the disk to experience torques about itself. This torque provides an explanation of how the inclination angle is maintained.

To explain the consistently positive inclination angles, we analyze a simplified cross section of the unbent disk, taken as a strip. The conservation of the angular momentum is given by

$$\mathbb{J} \vec{\Omega}' + \vec{\Omega} \times \mathbb{J} \vec{\Omega} = \vec{\tau}_p + \vec{\tau}_v, \quad (26)$$

where $\mathbb{J}$ is the moment of inertia, and $\vec{\tau}_p$ and $\vec{\tau}_v$ are the pressure and viscous torques, respectively. Since the angular velocity is prescribed as constant, the first term vanishes. For the simple shape we consider, the inertial term $\vec{\Omega} \times \mathbb{J} \vec{\Omega}$ is also zero due to $\mathbb{J}$ being diagonal. For the actual disk shape, this term is not strictly zero; it scales with Ω^2 and, therefore, cannot account for the symmetry breaking in the measured inclination angle. Reversing $\vec{\Omega}$ to $-\vec{\Omega}$ at a given inclination angle α is equivalent to reversing α to $-\alpha$ at fixed Ω , and in both cases, the dynamics remain unchanged.

We consider a simplified configuration to analyze the two remaining torques about the strip's center: those due to the hydrodynamic pressure gradient, $\vec{\tau}_p$, and the viscous stress from slip relative to the local flow, $\vec{\tau}_v$. In this configuration, the strip orbits outside the vortex core, $r_{\text{traj}} > 1.12 \sigma$, inclined at an angle α to the orbital path, rotating with angular velocity Ω .

In a Lamb-Oseen vortex, the radial pressure gradient is strictly inward and positive. Outside the vortex core, the radial pressure gradient decreases with distance from the vortex's center. Across a thin, inclined strip of thickness h , the pressure difference scales as $\Delta P \sim h (\hat{n} \cdot \hat{r}) \frac{\partial P}{\partial r}$ and acts locally in the radial inward direction. The inner half of the strip experiences a stronger pressure gradient, producing a greater resultant force which is closer to orthogonal with respect to its moment arm, while the outer half experiences the opposite, yielding a net torque, τ_p . For small $|\alpha|$, the net pressure torque is an odd function of α : it is clockwise for $\alpha < 0$ and counterclockwise for $\alpha > 0$.

Measurements show a small negative slip between the disk and the local fluid, indicating that the disk lags behind the surrounding flow by $|\delta| \sim 10^{-2}$. In this case, the outer half of the strip ($r > r_{\text{traj}}$) moves faster than the local fluid, producing a force approximately aligned with $-\hat{e}_\theta$ (exactly aligned for a dumbbell particle model), while the inner half ($r < r_{\text{traj}}$) moves slower, with a force in $\hat{e}_\theta$. Since viscous stresses act parallel to the local azimuthal direction, the resultant force on the inner half is more aligned with its moment arm than on the outer half, generating a clockwise viscous torque set by $\delta < 0$.

For $\alpha < 0$, the pressure torque and the viscous torque are both clockwise, as seen on the left side in Fig. 9. Acting in the same sense, they reinforce each other, allowing no balance to be reached for the disk. As a result, a negative inclination cannot be sustained. For $\alpha > 0$, the pressure torque is counterclockwise while the viscous torque remains clockwise, as seen on the right side in Fig. 9. In this case, the two contributions oppose each other, allowing the two torques to strike a balance.

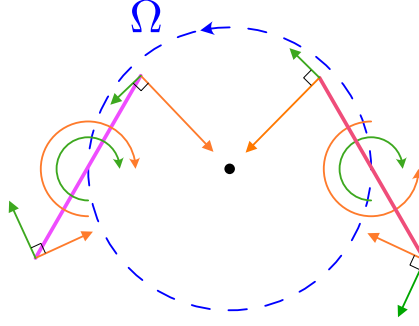


FIG. 9. Qualitative illustration of torque balances on a simplified flat strip. Straight arrows at the strip extremities illustrate the local forces: pressure (orange) directed radially inward toward the vortex center, and viscous stress (green) directed azimuthally. Curved arrows show the corresponding resulting torques. For $\alpha < 0$ (left), both pressure and viscous torques are clockwise (reinforcing), while for $\alpha > 0$ (right), the pressure torque is counterclockwise and the viscous torque is clockwise (opposing), permitting a balance at a finite positive α .

Therefore, a finite positive inclination angle can be maintained in equilibrium. This opposing torque mechanism explains why only positive inclination angles are observed in the experiments.

This observation of a resulting torque is not taken into account explicitly in the model. As such, the local shape of the disk in the model is not modified, instead remaining with a constant radius of curvature for our analysis.

To examine the model's sensitivity to the angle of inclination, Fig. 10(a) presents the contours of vanishing force as a function of α for $R = 12$ mm and $\Omega_F = 11$ Hz. For small inclinations

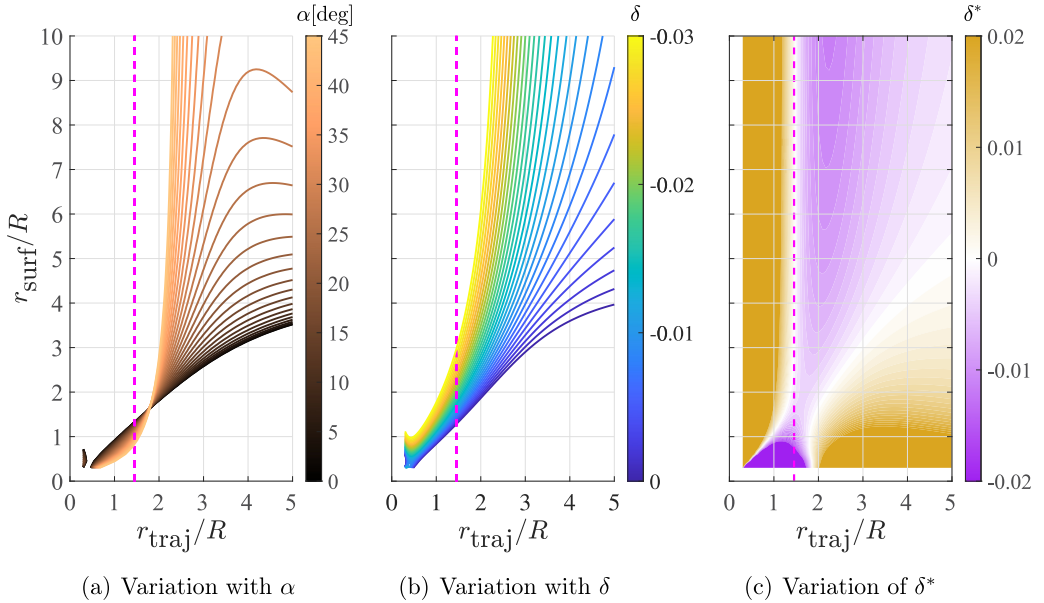


FIG. 10. Parametric sensitivity of the vanishing force contours with respect to the orientation and slip parameters. Figure 10(a) shows vanishing force contours as a function of inclination angle α for $R = 12$ mm and $\Omega_F = 11$ Hz, computed without slip. Figure 10(b) shows the contours as a function of slip ratio $\delta = \Delta u_s / u_\theta$, with α fixed at the averaged value of $\bar{\alpha} = 12.3^\circ$ for $R = 12$ mm. Keeping the same $\bar{\alpha}$, Fig. 10(c) illustrates the variation of δ^* . The dashed magenta line [] corresponds to the core size $\sigma(\Omega_F)/R$ for reference.

($\alpha \lesssim 10^\circ$), the contours remain close to the base model and are roughly linear for $1 \leq r_{\text{traj}}/R \leq 3$. As α increases, the contours become progressively more nonlinear. A quasifixed point persists near $r_{\text{traj}}/R \approx 1.8$, corresponding to the location of maximum fluid velocity and, in turn, the maximum pressure gradient. At this point, the inclined disk experiences nearly balanced pressure gradient contributions across its inward- and outward-tilting halves. In any case, reproducing the experimental trend would require an inclination angle on the order of 40° , which is much larger than the measured values. This parameter alone, therefore, cannot account for the observations.

C. Extended model: Inclination with slip velocity

The velocity measurement of the disk, along with its inferred radial position with respect to the vortex's center, reveals that there is a slip velocity between the disk and the fluid. The slip velocity is introduced into the model by modifying the centrifugal force term, where the slip velocity is defined as $\Delta u_s = \delta u_\theta$, following Eq. (20). Figure 8(c) presents the resulting shift when introducing a slip velocity of $\delta = -2\%$. The measured conformation and position are in fair agreement with the vanishing force contour lines, where the disk is expected to find an equilibrium.

Currently, measurements only allow for a qualitative estimation of the slip velocity as the instantaneous velocity field of the fluid is not accessible during the reconstruction measurements. Holding $\alpha = 12.3^\circ$ fixed, a parametric sweep of the slip velocity, $\delta = \Delta u_s/u_\theta$, is shown in Fig. 10(b). As the magnitude of the slip increases, the contours of vanishing force shift upward in the $(r_{\text{traj}}, r_{\text{surf}})$ plane, indicating that a lower degree of surface curvature is required to maintain equilibrium at a given orbital radius. The contour of vanishing force exhibits noticeable shifts even for small variations in $\Delta u_s/u_\theta = \delta$, highlighting the sensitivity of the predicted equilibrium configuration to slip.

To estimate from our model the magnitude of the slip velocity, we calculate a surface-averaged disk velocity:

$$\bar{u} = \frac{1}{\pi R^2} \int_S u_\theta(\vec{x}_p) dA, \quad (27)$$

where the local flow velocity, $u_\theta(\vec{x}_p)$, is averaged over the surface of the disk in a given configuration $(R, r_{\text{traj}}, r_{\text{surf}}, \alpha)$. From this average velocity, $\bar{u}$, a corresponding slip velocity is then defined as

$$\delta^* = \frac{\bar{u} - u_\theta(r_{\text{traj}})}{u_\theta(r_{\text{traj}})} = \frac{\Delta \bar{u}_s}{u_\theta(r_{\text{traj}})}. \quad (28)$$

Fixing $\alpha = 12.3^\circ$, the variation of δ^* is shown in Fig. 10(c). The regions where $\delta^* \leq 0$ (violet), where $\bar{u}$ is smaller than $u_\theta(r_{\text{traj}})$, qualitatively align well with the experimental observations in Fig. 5(c).

Following this, $\mathcal{F}$ is evaluated for the extended model using the average values of Ω_F and $\bar{\alpha}$ along with the resulting $\bar{u}$ for the centrifugal term for each disk size.

Figure 11 shows that the disk-averaged results for the extended model align with the experimental measurement from Fig. 5. The bands of vanishing forces agree fairly well with the measurements. The measured data seem to cluster closer to the vanishing force line, as in Figs. 11(b) and 11(c). As R of the flexible disk increases, we see the disk being able to sustain greater surface curvatures, relative to its radius, while orbiting closer to the vortex core.

VII. CLOSING REMARKS

This work investigates the trapping of heavy-flexible disks near a strong vortex. The experimental measurements show that, contrary to rigid spherical particles, heavy-flexible disks can be trapped, in a quasistable orbit, around a strong vortex. This observation was measured through the 3D reconstruction and tracking of the disk. To better understand the underlying physics behind this phenomenon, a reduced model was developed where the hydrodynamic pressure force was balanced with centrifugal force by using a Lamb-Oseen vortex to model the flow field. The parameters used

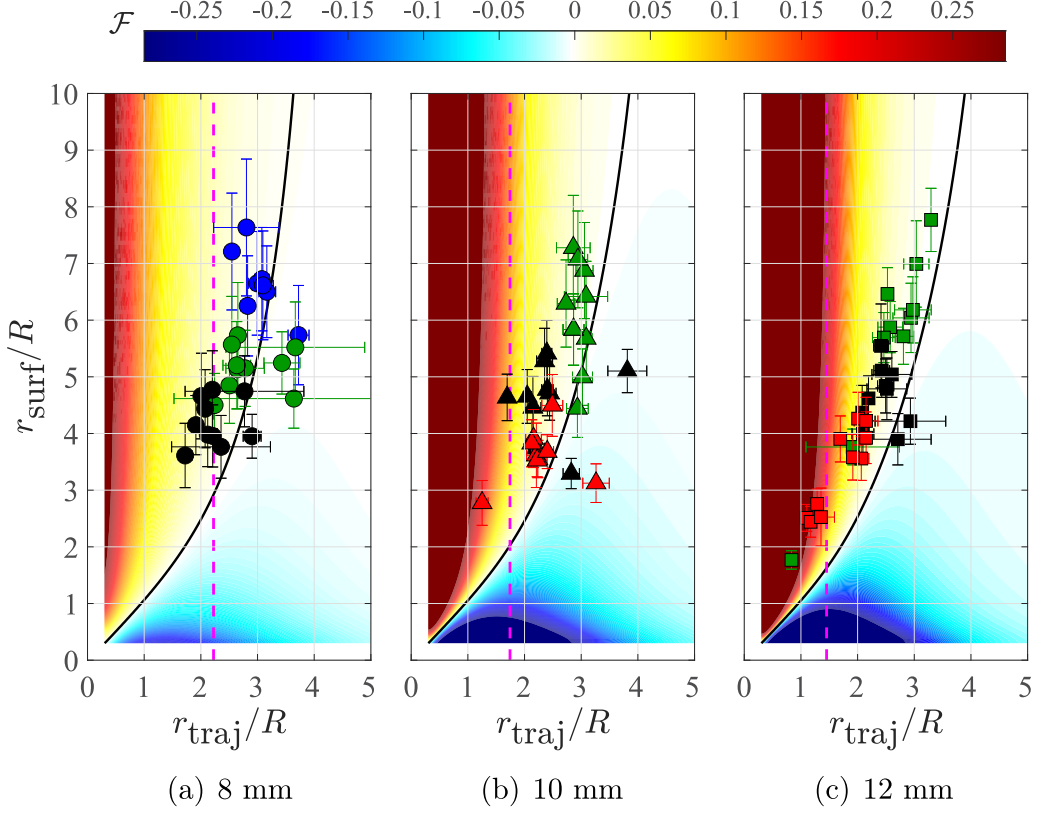


FIG. 11. The normalized net force, $\mathcal{F}$, with respect to r_{traj} and r_{surf} for the extended model with the corresponding measurements for $R = 8, 10$, and 12 mm are presented in Figs. 11(a)–11(c), respectively. The dashed magenta line [—] corresponds to the core size $\sigma(\bar{\Omega}_F)/R$, where $\bar{\Omega}_F$ is the mean forcing frequency for a given disk size, and the black contour line [—] traces where the net force vanishes to zero.

to define the vortex were prescribed based on a separate PIV characterization of the flow field. The key parameters observed to play a role in reaching an equilibrium included the disk's radial position, r_{traj} , surface curvature, r_{surf} , angle of inclination, α , and the small slip velocity between the disk and the local fluid. A good agreement between the measurements and the reduced model was obtained for the position, r_{traj} , and shape, r_{surf} , of the disk. In all trapping events, the measurements show the disks have a positive angle of inclination, α . It is observed that during a trapping event, the disks have r_{surf} , which is greater than r_{traj} by around a factor of 2. The differences between this work and that conducted on symmetric rigid particles indicate a need and open call for further investigation into the variation of dispersion and transport of flexible anisotropic particles in regions of high vorticity (as in the case of plastics in turbulence environmental flows).

Our measurements show that a combination of the anisotropy and the deformability of the flexible-heavy disk plays a crucial role in allowing trapping near regions of high vorticity. The work of [19] showed that heavy point particles tend to avoid regions of high vorticity, which follows the intuitive thinking that heavy spherical particles would be centrifuged and expelled from regions of high rotation. Surprisingly, we observed these heavy flexible disks being trapped near the region of high vorticity where the radius of the disk's orbits is comparable to the size of the vortex core. This contrast raises the question of how thin anisotropic microplastics could aggregate differently than spherical particles in the presence of vortical filaments of comparable scale.

In [3], particles are noted to be pushed away from regions of high acceleration, which is linked to where the modulus of the pressure gradient is locally high. This tendency is the opposite of what we see in our measurement of flexible disks. Across the range of disk size and vortex strength investigated, we observed that the disks were preferentially trapped at radial positions from the apparent axis of rotation. This radial position is in fair agreement with the local velocity maximum when considering the Lamb-Oseen vortex model, which is interchangeable with the location of the maximum modulus of the pressure gradient. This, once again, stresses the need to take into account the shape factors of the particles when analyzing how heavy particles are influenced by regions of high vorticity.

In theoretical and numerical approaches, there are cases where it appears possible for vortices to have stable regions for symmetry-breaking particles that interact over a finite length scale. In [8], dumbbell particles are shown to have stable spirographic orbits around a Lamb-Oseen vortex. When placing the dumbbell particles in a flow field generated by a Sutherland vortex model, a strong band of clustering appears at a radius linked to the maximum velocity, as found in our experiments.

Our measurements have shown that the heavy-flexible disk is required to have a positive angle of inclination with respect to the axis of rotation during the trapping event. In [9], a neutrally buoyant deformable particle in the presence of a Taylor-Green vortex is attracted to the center of the vortex. To decouple the effects of the deformable interface of the fluid particles, they further found that a thin neutrally buoyant oblate ellipsoid, a shape that is reminiscent of a disk, would orbit the axis of the vortex with cyclic variations in the particle's angle of inclination with respect to the particle's trajectory. They observed that intervals in time corresponding to positive angles of inclination, as we defined in our work, were well correlated with instances where the particle migrated toward the center of rotation. This tendency is strongly reflected in our experimental measurements: every time we observed a trapping event, the orientation of the particles was inclined toward the direction of the vortex. Given that our particles are heavy with their own inertia with respect to the fluid around them, the angle of inclination, along with its finite anisotropic shape, allows it to have degrees of freedom to trap at stable orbits.

Further work is desired to obtain instantaneous measurements of both the flow field and the disks. Simultaneous measurement would also provide answers regarding the difference in velocity between the disk and the flow, which was left in the model as a constrained fitting parameter. Instantaneously measuring the slip velocity would help better account for the effects of viscosity. By obtaining a more complete understanding of the local forces, further insight into the preferred configurations could be gained. This would involve not only considering the condition of zero net force on the disk, but also taking into account the pitching torques on the disk and how it relates to α .

The theoretical model currently presented does not consider the flexibility of the disk, but rather its shape. To decouple this effect, a bent rigid disk with $R = 8$ mm, specific gravity of 1.2, thickness $h = 750$ μm , and surface curvature $r_{\text{surf}} = 8$ mm was fabricated and tested. No trapping event was observed, even after an extended period of observation. While we do not rule out the possibility that thin, rigid, precurved particles can become trapped in a quasistable orbit, we expect that reaching the appropriate configuration is more difficult without the ability to deform in response to the flow. Although flexibility is not required, it does allow the disk to adapt its form more readily to find itself in a stable orbit. However, in practice, the flexibility of the disk is seen to play a crucial role in reaching the trapping state and stability of the orbit. To reach the equilibrium position, the disk typically approaches from one of two different states. In one approach, the disk migrated radially inward from the slow-moving regions of the tank toward the vortex, gradually changing its shape as it reached the equilibrium position. In the other approach, the disk would be ingested by the rotation of an impeller, then sent through the center line of the vortex in a compact shape. Subsequently, the disk would then change its shape and be ejected away from the center of the vortex toward the radial position of the orbit. In both cases, the disk's shape evolved based on the stresses experienced in the flow.

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DATA AVAILABILITY

The processed data used to generate the figures in this article are publicly available at [20]. The raw data supporting the findings of this article are not publicly available upon publication because making them publicly accessible is not technically feasible, and/or because the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The raw data are available from the authors upon reasonable request.

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- [1] E. van Sebille, S. Aliani, K. L. Law, N. Maximenko, J. M. Alsina, A. Bagaev, M. Bergmann, B. Chapron, I. Chubarenko, A. Cózar, P. Delandmeter, M. Egger, B. Fox-Kemper, S. P. Garaba, L. Goddijn-Murphy, B. D. Hardesty, M. J. Hoffman, A. Isobe, C. E. Jongedijk, M. L. A. Kaandorp, *et al.*, The physical oceanography of the transport of floating marine debris, *Environ. Res. Lett.* **15**, 023003 (2020).
 - [2] F. Toschi and E. Bodenschatz, Lagrangian properties of particles in turbulence, *Annu. Rev. Fluid Mech.* **41**, 375 (2009).
 - [3] J. Bec, L. Biferale, M. Cencini, A. Lanotte, S. Musacchio, and F. Toschi, Heavy particle concentration in turbulence at dissipative and inertial scales, *Phys. Rev. Lett.* **98**, 084502 (2007).
 - [4] G. A. Voth and A. Soldati, Anisotropic particles in turbulence, *Annu. Rev. Fluid Mech.* **49**, 249 (2017).
 - [5] E. Huseby, J. Gissinger, F. Candelier, N. Pujara, G. Verhille, B. Mehlig, and G. Voth, Helical ribbons: Simple chiral sedimentation, *Phys. Rev. Fluids* **10**, 024101 (2025).
 - [6] T. Miara, C. Vaquero-Stainer, D. Pihler-Puzović, M. Heil, and A. Juel, Dynamics of inertialess sedimentation of a rigid U-shaped disk, *Commun. Phys.* **7**, 47 (2024).
 - [7] C. Vaquero-Stainer, T. Miara, A. Juel, D. Pihler-Puzović, and M. Heil, U-shaped disks in Stokes flow: Chiral sedimentation of a non-chiral particle, *J. Fluid Mech.* **999**, A71 (2024).
 - [8] S. R. Yerasi, R. Govindarajan, and D. Vincenzi, Spirographic motion in a vortex, *Phys. Rev. Fluids* **7**, 074402 (2022).
 - [9] Y. Fujiki, H. Awai, Y. Motoori, and S. Goto, Attraction of neutrally buoyant deformable particles towards a vortex, *Phys. Rev. Fluids* **9**, 014301 (2024).
 - [10] J. Picardo, R. Singh, S. Ray, and D. Vincenzi, Dynamics of a long chain in turbulent flows: Impact of vortices, *Phil. Trans. R. Soc. A* **378**, 20190405 (2020).
 - [11] A. Heyes, R. Jones, and D. Smith, in *Proceedings of the 12th International Symposium on Applications of Laser Techniques to Fluid Mechanics* (Lisbon, Portugal, 2004), pp. 35–43.
 - [12] H. Lamb, *Hydrodynamics* (Dover Publications, New York, 1945).
 - [13] N. T. Ouellette, H. Xu, and E. Bodenschatz, A quantitative study of three-dimensional Lagrangian particle tracking algorithms, *Exp. Fluids* **40**, 301 (2006).
 - [14] J. Duchon, Interpolation des fonctions de deux variables suivant le principe de la flexion des plaques minces, *Revue française d'automatique, informatique, recherche opérationnelle, Analyse numérique* **10**, 5 (1976).
 - [15] A. Bartoli, M. Perriollat, and S. Chambon, Generalized thin-plate spline warps, *Int. J. Comput. Vis.* **88**, 85 (2010).
 - [16] E. Abbena, S. Salamon, and A. Gray, *Modern Differential Geometry of Curves and Surfaces with Mathematica* (Chapman and Hall/CRC, Boca Raton, 2017).

- [17] E. Ibarra, A. Bartoli, and G. Verhille, 3D reconstruction of a thin flexible disc in a vortical flow, [Exp. Fluids](#) **64**, 172 (2023).
- [18] A. U. M. Masuk, A. K. Salibindla, and R. Ni, The orientational dynamics of deformable finite-sized bubbles in turbulence, [J. Fluid Mech.](#) **915**, A79 (2021).
- [19] E. Calzavarini, M. Cencini, D. Lohse, and F. Toschi, (International Collaboration for Turbulence Research), Quantifying turbulence-induced segregation of inertial particles, [Phys. Rev. Lett.](#) **101**, 084504 (2008).
- [20] G. Verhille, E. Ibarra, and F. Candelier, Dataset of “Trapping of a flexible disk in a vortical flow: Reconstruction process, measurements, and theory”, Recherche Data Gouv (2026), <https://doi.org/10.57745/AICRNL>.