Size and shape dependent rotation characteristics of thin film ultrasonic rotors

Cite as: Appl. Phys. Lett. 121, 254102 (2022); doi: 10.1063/5.0126000
Submitted: 14 September 2022 · Accepted: 10 December 2022 · Published Online: 21 December 2022

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ABSTRACT
The controlled rotation of acoustically levitated samples is beneficial for analyzing sample properties, e.g., in a recently reported room temperature x-ray diffraction experiment, wherein thin film sample holders comprising thin film disks with short blades attached around their circumference were utilized. However, the mechanism of producing the torque and the determinant factor of the rotation direction for these planar ultrasonic rotors have been elusive. We, therefore, study the impact of the size and shape on the rotation characteristics of these ultrasonic rotors in air and further study the influence of the viscosity of fluid. Theory and experiment demonstrate the essential role of the short blades in producing the acoustic torque both in air and water. In the airborne case, the shape and arrangement of the blades are found to determine the rotation direction. In water, with a dynamic viscosity 55 times higher than that of air, we demonstrate that ultrasonic rotors down to 25-μm-disk-diameter function in an optimized experimental geometry with approximately the same actuation efficiency as in air. Our results will be beneficial to further improve the applicability of the ultrasonic rotors as sample holders for airborne experiments and to explore the micrometer-scale ultrasonic rotors in liquid.

When a sample is exposed to an acoustic radiation or levitated in an acoustic standing wave, torque is produced by the coupling of the acoustic radiation pressure with the sample shape. This has been also utilized to measure the acoustic pressure by the so-called Rayleigh disk, wherein the torque around the axis in the disk plane and perpendicular to the acoustic radiation gives the acoustic pressure.1,2 In acoustic levitation experiments, the acoustic torque may cause not only random rotation but also positional instability and ejection from the levitator. To circumvent this obstacle, samples with symmetric shapes are normally adopted. The sample rotation can be also suppressed by modulating the acoustic field3–11 but at the cost of increasing complexity of drivers and transducers, limiting their use for special purposes.

The sample rotation is favorable for applications such as the x-ray12,13 or neutron diffraction experiments14 and active mixing in microfluidic channels.15,16 However, in comparison to the Rayleigh disk, the acoustic torque exerted on a thin disk around the rotation axis perpendicular to the disk plane has been hitherto less studied. Recently, polymer thin film disks with short blades on their circumference have been reported as holders for protein crystal samples for conducting x-ray diffraction experiments.13 The controllable rotation and the high positional stability of these ultrasonic rotors were the key to the dataset collection without using goniometers. However, the mechanisms to generate the torque and to determine the rotation direction have been elusive. Since the acoustic torque violates the axi-symmetry of the thin-films around the axis of the acoustic levitator, the residual and chiral asymmetry of the film17 and the resultant coupling of the acoustic radiation pressure to the blades were considered as the possible origin. Given the absence of the circulation of the acoustic field in our setup,13 viscous torque18–21 or acoustic streaming were not thought to be responsible.

In this work, we, therefore, experimentally study the rotation characteristics of these polymer thin-film ultrasonic rotors as functions of the rotor size and blade shape. The results show that the short blades convert the acoustic pressure gradient exerted on their periphery to the torque. Another aim of the present study is to explore the
The ultrasonic rotors were fabricated by UV photolithography using a direct laser writer (DWL66+, Heidelberg Instruments). The fabrication procedure is as follows. On a Si wafer, we first spin-coat a 1.3-μm-thick sacrificial layer (LOR-10B, MicroChem Corp.) and a negative resist layer, mr-DWL 40 or mr-DWL 5 (Micro Resist Technology, GmbH). Next, the ultrasonic rotor patterns were exposed by scanning a UV laser. Finally, the development in mr-Dev 600 (Micro Resist Technology, GmbH) follows. To harvest the samples, we dissolve the residues of the sacrificial layer by gentle sonication in MF-26. Table I summarizes parameters of all the fabricated ultrasonic rotors.

For the airborne acoustic rotation experiment, we used a single-axis levitator with the ultrasound frequency of 40.6 kHz [see Fig. 1(e), the acoustic wavelength \( \lambda = 8.45 \text{ mm} \) in air]. The acoustic cavity of the levitator comprises a horn with the diameter of 20 mm attached to the bolt-clamped Langevin-type transducer and a concave spherical mirror reflector with a 20-mm focal distance. We adjusted the cavity to the fifth resonance, with the horn-to-mirror separation being approximately 5\( \lambda \)/2. The ultrasound pressure was applied continuously while maintaining the transducer resonance by frequency feedback. We monitored the levitation and the rotation of the ultrasonic rotors by a high-speed camera (Photron mini AX100) with a zoom lens overlooking the samples with a viewing angle \( \theta = 15^\circ \). The average acoustic pressure in the acoustic cavity was monitored by a sensor fixed at the mirror reflector (see supplementary material). The measured acoustic pressure was normalized by the levitation threshold pressure (corresponding to 1.35 kPa rms) for small (\(<0.5\) mm) water droplets measured with the same levitator setup.25

For the experiments in water, we immersed the ultrasonic rotors in a water bath fabricated on a standard glass slide and observed those by a microscope from beneath the glass slide. The magnified images were recorded by a CCD camera with the frame rate in the range of 10–130 Hz. Ultrasound at the frequencies of 2.3, 4.7, 8.5, and 13 MHz

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**TABLE I. List of the studied ultrasonic rotors.**

<table>
<thead>
<tr>
<th>Name</th>
<th>Diameter of the disk part (μm)</th>
<th>Nominal thickness (μm)</th>
<th>Blade shape/arrangement</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>4000</td>
<td>22</td>
<td>Square/symmetric</td>
</tr>
<tr>
<td>R2</td>
<td>400</td>
<td>22</td>
<td>Square/symmetric</td>
</tr>
<tr>
<td>R3</td>
<td>200</td>
<td>22</td>
<td>Square/symmetric</td>
</tr>
<tr>
<td>R4</td>
<td>4000</td>
<td>22</td>
<td>No blade</td>
</tr>
<tr>
<td>R5</td>
<td>4000</td>
<td>22</td>
<td>Single-side-rounded/chiral</td>
</tr>
<tr>
<td>R6</td>
<td>4000</td>
<td>22</td>
<td>Single-side-rounded/two facing blades are flipped</td>
</tr>
<tr>
<td>R7</td>
<td>100</td>
<td>22</td>
<td>Square/symmetric</td>
</tr>
<tr>
<td>R8</td>
<td>75</td>
<td>5</td>
<td>Square/symmetric</td>
</tr>
<tr>
<td>R9</td>
<td>50</td>
<td>5</td>
<td>Square/symmetric</td>
</tr>
<tr>
<td>R10</td>
<td>25</td>
<td>5</td>
<td>Square/symmetric</td>
</tr>
</tbody>
</table>

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was applied by different transducers, each of which emits focused ultrasound from the spherical convex end-surface with 6 mm radius of curvature [12,13] [see Fig. 4(a)]. As shown in Fig. 4(b), ultrasound pulses produce circular pressure nodes on the plane of the glass slide with the nominal separation close to \(\lambda/2\) of the ultrasound [\(\sim 80 \mu m\) in Fig. 4(b) excited by 13 MHz ultrasound pulses] as visualized by the aggregation of the tracer particles (\(\sim 3 \mu m\) polyethylene spheres). UV and white LED were used to illuminate fluorescent particles and ultrasonic rotors, respectively. We also evaluate the acoustic pressure distribution of the tracer particles (CCW) arrow in Fig. 2(c) (see Video 1 of the supplementary material). The rotation direction of R5 is flipped to clockwise (CW) when it is flipped (see Video 2 of the supplementary material) with approximately the same rotation characteristics as shown in Fig. S3(a) of the supplementary material. Interestingly, the rotation characteristics of R3 is approximately the same as that of R1, as shown in Fig. 2(f). When the two of the rounded-edge blades were flipped as in R6, the rotation direction became again incidental as R1, even reverted upon switching the pressure (when the pressure was below approximately 0.6). In the range \(P < 0.23\), R6 did not rotate (see Video 3 of the supplementary material). We note that the ultrasonic rotors studied in the present work can be rotated at \(f_r\) in the range of 0–1 rps from \(P\) near the levitation threshold. This is in contrast to the thin films reported previously. As shown in Eq. 4 of the supplementary material, to initiate the rotation for the rotors with higher roughness, we need to apply \(P\) much higher than \(P_{th}\) and in between only oscillation but no rotation is observed.

For comparison, we calculated the acoustic pressure distribution around R5 by solving the transient Navier–Stokes equations numerically, the computational fluid dynamics (CFD) code ANSYS Fluent 2021R2 being used for this. The output of the ultrasound transducer was assumed to be 59.4 Pa rms, corresponding to \(P\) of 0.35 in our acoustic levitator. For simplicity, the ultrasonic rotor was assumed to be a rigid body and fixed to the space at the center of the middle node. Further details of the simulation are described in the supplementary material. Figure 3(a) shows the iso-surfaces of the time averaged...
pressure, in which blue and yellow surfaces display 1 Pa below and above the atmospheric pressure, respectively. The top-view of the instantaneous surface pressure distribution relative to the ambient pressure is shown in Fig. 3(b) together with the stream lines around the blade. The timing was when the pressure integrated over the disk surface became maximum. We noticed a higher pressure on the rounded side of the blade than the straight side at the same lateral coordinate, as indicated by the dashed circles in Fig. 3(b). The pressure on the side of the blade is similar to that on the top surface, which results in the acoustic torque in CCW. The higher pressure on the rounded side (the lower dashed circle) is considered to be caused by the gathering of the flow in the downstream, which is depicted by the blue arrows in Fig. 3(b).

From the CFD simulation, we calculated the time-averaged acoustic torque $T^{(\text{CFD})}$ exerted on R5 scaled for $P = 0.25$ and found a value equal to $2.9 \times 10^{-10}$ N m. For comparison, we evaluate the acoustic torque $T^{(\text{exp})}$ under the experimental conditions by noting that at the steady state, $T^{(\text{exp})}$ is equal to $2 \pi f_s \Gamma$, where $\Gamma$ is the rotational friction. To calculate $\Gamma$, we consider two approximations for our ultrasonic rotor by a thin disk and by a crossed-cylinder, given the key role of the short blades in producing the acoustic torque. We found that the former results in $T^{(\text{exp})}$ an order of magnitude smaller than $T^{(\text{CFD})}$. In the latter case, we found that $T^{(\text{exp})}$ was equal to $(1.34 - 4.02) \times 10^{-10}$ N m for $f_s$ of 1–3 rps, in reasonable agreement with $T^{(\text{CFD})}$.

From the close examination of the CFD result, we found that 76% of $T^{(\text{CFD})}$ is given by the acoustic radiation pressure and the remaining 24% by the viscous shear stress. However, the contribution of the viscous torque is negligible in our experiment due to the absence of the circulation of the air as shown by the flow visualization experiment reported previously.

We now discuss the behavior of the ultrasonic rotors in water. As depicted in Figs. 4(a) and 4(b), an in-plane standing wave is created by placing the emitting face of the transducer close to the bottom of the water bath (glass slide). We found that when the transducer–glass distance was 1.9 mm and the ultrasonic rotor size is approximately equal to $\lambda/2$ (the pitch of the standing wave nodes) as shown in Fig. 4(b), the acoustic torque was enhanced. We were able to rotate R9 and R10 with the diameters of 50 and 25 $\mu$m, respectively, by aligning those in the same way (see Videos 4 and 5 of the supplementary material). Since the acoustic radiation force varies sinusoidally in the radial direction, the blades on the opposite side can pick up the acoustic torque in the same direction. Each blade is exerted by an azimuthal force, which is produced by the difference of the acoustic radiation pressure between the two sides of a blade (see the supplementary material for the detection of the sinusoidal variation of the acoustic radiation force and the evaluation of $P_a$ by the pulsed motion and the Brownian motion of tracer particles). We found that, although the rotation direction depends on the incidental initial azimuthal angle of the blades relative to the node lines, full turns of rotation were observed even with the rotors down to the disk diameter of 25 $\mu$m (R10) with its size approaching that of biological cells. We were also able to rotate the R2 and R3 which have been studied in air (Fig. 1) at the lowest frequency of 2.3 MHz.

We note that in the airborne experiment, the $E_{\text{ac}}$ required to rotate the ultrasonic rotors (R1 with the disk diameter of 4 mm in 40 kHz ultrasound) at $f_s$ of 1 rps was equal to 8.5 J/m$^3$. In comparison, we found that for rotating R8 at the same $f_s$ by 8.5 MHz ultrasound, $E_{\text{ac}}$ is equal to $5.3 \pm 0.5$ J/m$^3$. Therefore, the rotation efficiency as measured by the ratio of $f_s$ to $E_{\text{ac}}$ is of the same order of magnitude for the two cases despite the difference in the ultrasound frequency by a factor of 212 and the difference in the viscosity by a factor of 55.

In summary, we elucidate the mechanism to generate the acoustic torque exerted on our airborne ultrasonic rotors by experiment and numerical simulation. This is a step forward to further optimize those as sample holders for protein crystallography applications. In addition, we demonstrate miniaturized ultrasonic rotors down to 25 $\mu$m-disk-
diameter in highly viscous fluid (water). The acoustic energy density required to rotate the ultrasonic rotors at a same rotation speed is found to be approximately the same in water and in air. Different from imposing the angular momentum of the acoustic field via friction by using vortex beams \(^34\)–\(^36\) or viscous torque \(^11\)\(^,\)\(^24\), our result introduces a unique way of rotational manipulation of planar samples by the acoustic radiation pressure without resorting to three-dimensional fabrication \(^37\)\(^,\)\(^38\). The experimentally observed relationship between the rotor size and the ultrasound wavelength suggests a possibility to realize ultrasonic rotors that are a few micrometers or even smaller in diameter. The generation of sub-micrometer wavelength ultrasound is also feasible by surface acoustic wave transducers \(^39\)\(^,\)\(^41\). Nevertheless, the acoustic torque mechanism of the in-water ultrasonic rotors is yet to be fully elucidated; from the coupling mechanism indicated from the experiment, the direction of the acoustic torque is reverted at every quarter turn. As such, the fact that full turns were observed for these rotors suggests that the rotational inertia plays an important role, which may substantially diminish for the rotors with a few micrometer diameters. The experimental exploration of such few micrometer ultrasonic rotors is under way.

See the supplementary material for the description of the acoustic mirror of the levitator, the high speed rotation of the ultrasonic rotors R2 and R3; the snapshots of the ultrasonic rotors R1, R4, R5, and R6; the influence of flipping on the rotational characteristics of the ultrasonic rotor R5; the CFD simulation of acoustically levitated ultrasonic rotors in air; the measurement of the acoustic pressure in the ultrasonic rotor experiment in water; and video recordings of the rotation of the ultrasonic rotors, R5, flipped R5, and R6 in air, as well as R9 and R10 in water (supplementary material Videos 1–5).

The authors thank Roderick Y. H. Lim for thoughtful comments regarding the applications in nanobiology and G. V. Shivashankar for stimulating discussions on the applications in mechanobiology. S.J. was supported by the Swiss Nanoscience Institute Ph.D. School (Project No. P2007). This work was partially supported by the Swiss National Science Foundation No. 200021_192772.

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Shichao Jia: Conceptualization (equal); Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). Yohei Sato: Data curation (supporting);
Formal analysis (supporting); Investigation (equal); Methodology (supporting); Visualization (supporting); Writing – original draft (supporting); Writing – review & editing (supporting). Soichiro Tsujino: Conceptualization (equal); Formal analysis (equal); Funding acquisition (equal); Investigation (equal); Methodology (equal); Project administration (equal); Resources (equal); Supervision (equal); Writing – original draft (equal); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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