

Stereo-PIV Study of Drone Propeller Wakes for Noise Reduction

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Abstract

The aerodynamic wake of small UAV propellers plays a central role in both thrust generation and noise emission, yet the flow mechanisms linking propeller geometry to tonal and broadband noise are still not fully understood. In this study, stereoscopic particle image velocimetry (stereo-PIV) is used to investigate the three-component wake flow of several drone-scale propeller concepts in hover, with simultaneous thrust, RPM, and acoustic measurements performed in an anechoic chamber. A commercial 16×5.4 T-Motor propeller is compared with a high-fidelity 3D-printed replica, a trailing-edge serrated blade, a trailing-edge flocked blade, an asymmetric three-blade rotor, and two toroidal closed-loop designs. All configurations are evaluated at a constant thrust of 5 N to ensure a consistent aerodynamic-acoustic comparison.

The stereo-PIV measurements reveal clear geometry-dependent differences in wake coherence, tip-vortex formation, and turbulence intensity. The baseline propeller produces a narrow, symmetric wake with strong coherent tip vortices, whereas the 3D-printed replica shows earlier vortex break-down and enhanced small-scale fluctuations. Serrated trailing edges introduce only minor wake diffusion, while the flocked trailing edge causes severe separation and reduced propulsive efficiency. The asymmetric three-blade design weakens blade-passing tonal content by redistributing aerodynamic loading, producing a less periodic wake. The toroidal propellers suppress distinct tip-vortex cores and generate lower overall sound pressure levels, with the tri-loop configuration showing the most collimated and coherent wake structure. These results demonstrate how stereo-PIV can directly relate wake topology to acoustic behavior and provide flow-based guidance for the design of quieter UAV propellers.

1. Introduction

With the rapid spread of small aerial platforms such as unmanned aerial vehicles (UAVs) and consumer drones, the mitigation of propeller-induced noise has become a central research and regulatory challenge. As these systems increasingly operate in urban and residential environments, their acoustic emissions pose significant environmental, social, and operational constraints. The

physical mechanisms of propeller noise are complex, involving unsteady flow–structure interactions that produce both discrete tonal components, associated with blade-passing frequencies, and broadband noise arising from turbulent flow features. Understanding and isolating these mechanisms is essential for developing quieter propellers without compromising aerodynamic efficiency or thrust performance.

Propeller noise is typically categorized into two main types: *tonal noise*, characterized by discrete frequency peaks, and *broadband noise*, which spans a continuous frequency spectrum. The principal sources of these emissions are summarized schematically in Figure 1. The dominant mechanisms include (e.g., Brooks et al., 1988; Candeloro et al., 2022):

1. **Blade–Vortex Interaction (BVI) noise:** resulting from the impingement of tip vortices on subsequent blades.
2. **Blade–Wake Interaction (BWI) noise:** caused by the interaction of a blade with the turbulent wake of preceding blades.
3. **Turbulent Boundary-Layer Trailing-Edge (TBLTE) noise:** generated by the interaction of a turbulent boundary layer with the blade’s trailing edge.
4. **Laminar Boundary-Layer Vortex-Shedding (LBLVS) noise:** associated with laminar separation bubbles and vortex shedding from smooth surfaces.

These mechanisms depend strongly on the local flow conditions along the blade span and vary with the propeller geometry, rotational speed, and Reynolds number (Deters et al., 2014; Zawodny et al., 2016). For small-scale UAV propellers operating at moderate Reynolds numbers, laminar boundary-layer vortex-shedding (LBLVS) and tip-vortex interactions (BVI) are particularly relevant (Grande et al., 2022; Meloni et al., 2023; Candeloro et al., 2022).

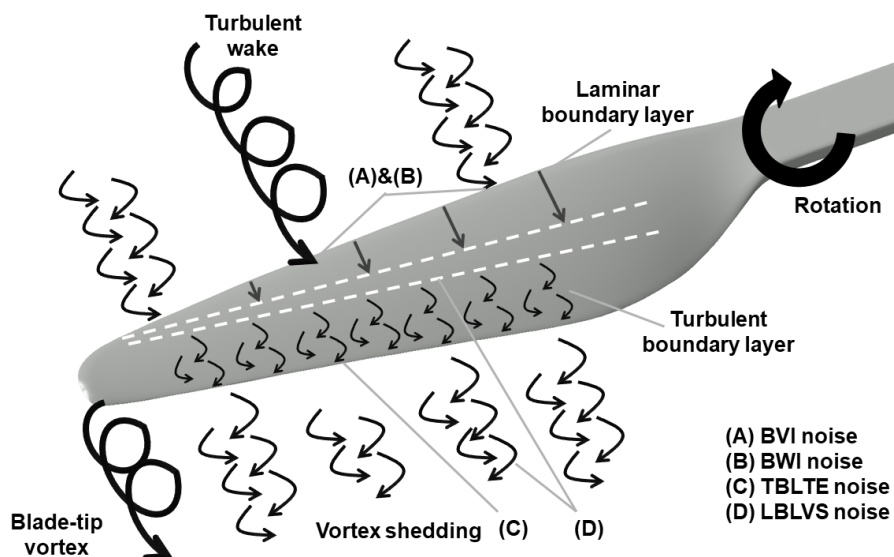


Figure 1. Schematic illustration of dominant propeller noise mechanisms: (A) BVI, (B) BWI, (C) TBLTE, and (D) LBLVS.

Thus, improving our understanding of the aerodynamic structures responsible for these noise components is key to designing low-noise propellers.

Recent work on rotor-noise reduction has largely focused on passive geometric and surface modifications that weaken coherent sources or de-phase tonal content. Trailing-edge and leading-edge serrations promote small-scale mixing and reduce broadband content (Avallone et al., 2018; Wei et al., 2020; Noda et al., 2022), while porous or compliant treatments alter trailing-edge scattering (Teruna et al., 2021). Surface microstructures such as microfiber (flocked) coatings have also been shown to suppress the broadband hump associated with laminar-separation-bubble dynamics on low-Re propellers (Hasegawa and Sakaue, 2024). Beyond edge and surface treatments, geometry-level strategies aim to disrupt periodicity or the formation of free tip vortices: asymmetric/uneven blade arrangements spread acoustic energy across neighboring harmonics, reducing blade-passing tones, whereas joined-blade or toroidal concepts close the tip to redistribute circulation and suppress helical tip-vortex shedding (Candeloro et al., 2022). Despite promising SPL reductions, there is still a need for detailed flow diagnostics that connect these design changes to wake topology and turbulence mechanisms—particularly under equal-thrust conditions.

The present study addresses this gap by comparing a commercial 16 inch T-Motor 16×5.4 carbon-fiber propeller, its high-fidelity 3D-printed replica, and several modified geometries: trailing-edge serrated (TES), trailing-edge flocked (TEF), an asymmetric three-blade rotor, and two toroidal (closed-loop) designs (bi-loop and tri-loop). All configurations are evaluated at equal thrust (5 N) to enable a fair aerodynamic-acoustic comparison. By correlating stereo-PIV velocity, vorticity, and fluctuation fields with simultaneously measured sound pressure levels (SPL), we assess how each geometric modification alters wake coherence, vortex dynamics, and the balance between tonal and broadband noise.

To this end, we employ **stereoscopic Particle Image Velocimetry (PIV)** to resolve the three-component velocity field in a vertical diametral plane through the rotor. Experiments are performed in *hovering mode* inside a custom anechoic chamber, with synchronized thrust, RPM, and acoustic measurements under controlled conditions. This integrated dataset allows us to link changes in wake topology—such as tip-vortex suppression, jet collimation, and turbulence levels—to observed differences in acoustic output across the tested propeller designs.

2. Experimental Setup

2.1. Propellers

The reference propeller employed in this study is a **T-Motor 16×5.4** carbon-fiber blade with a diameter of 16 in. Its geometry was captured using high-resolution 3D scanning and reproduced through additive manufacturing to create a **3D-printed replica**, which was tested alongside the original to evaluate the influence of surface quality and manufacturing precision on aerodynamic and acoustic performance. The scan data were imported into a CAD environment, where minor artefacts were removed, and the hub interface was adapted to match the experimental motor mount. The cleaned geometry was then manufactured using a thermoplastic matrix with embedded unidirectional carbon-fiber reinforcement oriented predominantly along the blade span. This layup provides high stiffness in the fiber direction while offering comparatively lower stiffness in the chordwise and out-of-plane directions.

Building upon this baseline design, a series of modified propeller configurations was developed to assess how geometric and surface alterations influence aerodynamic performance and noise

generation.

Trailing-Edge Serrated (TES) Propeller — Fabrication Method

The **TES propeller** introduces fine, arc-shaped serrations (approximately 0.6 mm in amplitude and spacing) along the trailing edge. To ensure geometric accuracy and structural integrity of the serrations, the serration pattern was first parametrically designed in *CATIA V5*, following a curvature-aligned arc pattern consistent with the blade's local camber line. The serrations were milled directly into the commercial carbon-fiber T-Motor blade using **CNC micromachining**, removing material from the trailing-edge region while preserving the surrounding aerodynamic geometry. This direct-modification approach was selected instead of fabricating 3D-printed replicas, as it avoids surface-roughness artefacts and ensures that any observed effects are attributable solely to the serration geometry rather than differences in material properties or manufacturing quality.

Trailing-Edge Flocked (TEF) Propeller — Fabrication Method

The **TEF propeller** incorporates a 6 mm-long layer of electrostatically flocked microfibers applied to the final 5 mm of the trailing edge. This fabrication approach is inspired by the methods reported by Meloni *et al.* (2023), where microfiber surfaces were used for passive noise reduction in low-Reynolds-number propellers.

To prepare the surface, the trailing-edge region of the baseline propeller was lightly abraded and cleaned with isopropanol to ensure proper adhesion. A thin uniform layer of conductive adhesive was then brushed onto the treated area. The microfibers (nylon-based flock, 6 mm length, 15–20 denier) were deposited using an **electrostatic flocking gun** operating at approximately 60–70 kV potential difference. During the flocking deposition, the propeller blade was held in a grounded fixture that oriented the electric field lines such that the fibers aligned preferentially along the local airfoil surface and trailing-edge direction. This flocking process provided a compliant, bio-inspired surface texture that mimics the downy microstructure of owl feathers, which are known to suppress vortex shedding and reduce aeroacoustic emissions.

Representative examples of these three configurations—the baseline, TES, and TEF propellers—are shown in Figure 2. An **asymmetric three-blade propeller** was also designed, consisting of two full-length blades and one shorter blade 3. This configuration is dynamically balanced about the rotation axis but produces an inherently non-uniform wake field (Fig. 3a).

Finally, two **toroidal propellers**—a bi-loop and a tri-loop design FPV (2023a,b), inspired by recent MIT prototypes Leclerc (2023)—were investigated (Fig. 3b and c). These closed-loop geometries eliminate the conventional blade tip and redirect vorticity into a continuous toroidal structure, reducing tip-vortex formation and associated noise.

All modified propellers were prototyped in-house via high-precision 3D printing or direct machining, depending on the configuration.



Figure 2. Baseline propeller and trailing-edge modified variants.

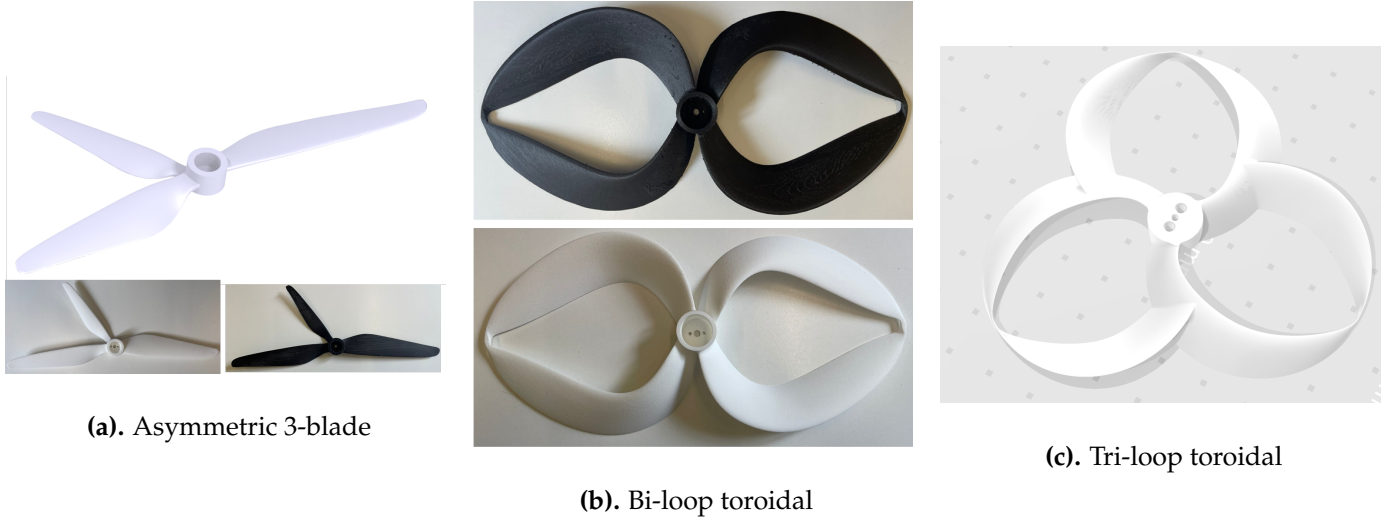


Figure 3. Experimental propeller configurations featuring non-conventional geometries.

2.2. Test Facility

Experiments were conducted in an indoor environment designed to minimize acoustic reflections. The propeller was mounted on a low-vibration electric motor inside a custom wooden anechoic chamber (see Fig. 4). The chamber consists of a wooden box of approximately 16 m³ volume, with airflow openings at both the top and bottom (20 cm on each side) to ensure smooth vertical flow through the test section without significant back pressure or recirculation. The chamber walls were covered with 5 cm acoustic foam to absorb sound. Thrust was measured with a one-dimensional force sensor (Baumer DLM20-IN.101.TP3.M4; Baumer, *Switzerland*) mounted below the motor, and the rotational speed (RPM) was obtained from ESC telemetry using a T-Motor *Alpha* 40A FOC brushless controller (6S, OPTO, 500 Hz; T-Motor, *China*). Three high-precision microphones (SINUS Mk202 with preamplifiers; SINUS Messtechnik GmbH, *Germany*) were arranged on a semicircular array of radius 0.85 m around the propeller (at 0° (axial), +45°, and −45° elevations) to measure the radiated sound pressure levels (SPL). The microphone signals were sampled at 51.2 kHz. For each propeller and operating condition, thrust, RPM, and acoustic data were recorded simultaneously over 8 s intervals. By comparing the sound spectra from different designs at equal thrust, we can identify how modifications impact tonal vs. broadband noise components.

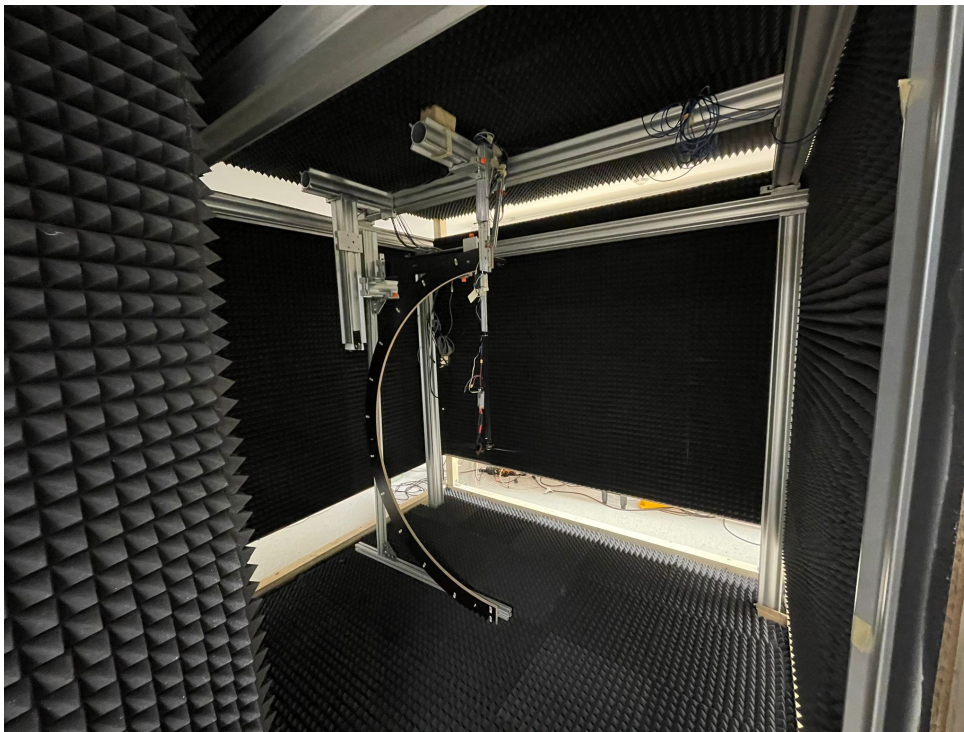


Figure 4. Interior of the anechoic chamber lined with 5 cm acoustic foam for noise suppression, providing a controlled environment for thrust, acoustic, and PIV measurements.

2.3. Stereo PIV System

A stereoscopic PIV setup was used to capture the three-component velocity field in a vertical plane through the propeller's wake. A dual-cavity Nd:YAG laser (Quantel Evergreen 200, 532 nm, ~ 200 mJ per pulse) generated a ~ 1 mm thick light sheet passing through the center of the rotor (illuminating a diametral plane that includes the rotation axis). DEHS seeding particles with a mean diameter of ~ 0.4 μm were introduced into the air to scatter the laser light. Two sCMOS cameras (LaVision Imager sCMOS, 5 megapixel) equipped with 100 mm Zeiss lenses (Zeiss Makro-Planar T* 2,0/100 mm) and Scheimpflug adapters (V3 from LaVision) were placed at approximate $\pm 30^\circ$ angles to the light sheet, each recording a different view for stereo reconstruction.

The cameras were synchronized by using a programmable timing unit (LaVision PTU X) with the laser pulses and operated in double-frame mode, capturing pairs of images separated by a short Δt (on the order of 20–40 μs) optimized for the expected flow velocities. The programmable timing unit and the motor's encoder were used to trigger the PIV acquisition at a fixed phase of the propeller rotation for some cases, ensuring repeatable capture of blade wake positions (for others, an asynchronous capture was used to sample randomly).

Approximately 1,000 image pairs were recorded for each propeller at the test condition of interest. A multi-pass cross-correlation algorithm (with final interrogation window size $\sim 32 \times 32$ px and 50% overlap) was applied to compute the instantaneous velocity fields (Using Davis 11, LaVision). The measurement resolution was about 0.1 mm/pixel, yielding vector spacing on the order of 1.5 millimeters in physical space. Calibration of the stereo camera system was performed using a dual-plane calibration target and standard pinhole calibration procedure, yielding an uncertainty of the in-plane velocity components below 2% of the tip speed (the out-of-plane component is

reconstructed with slightly higher uncertainty, $\sim 5\%$). Figure 5 illustrates the location of the Field of View schematically.

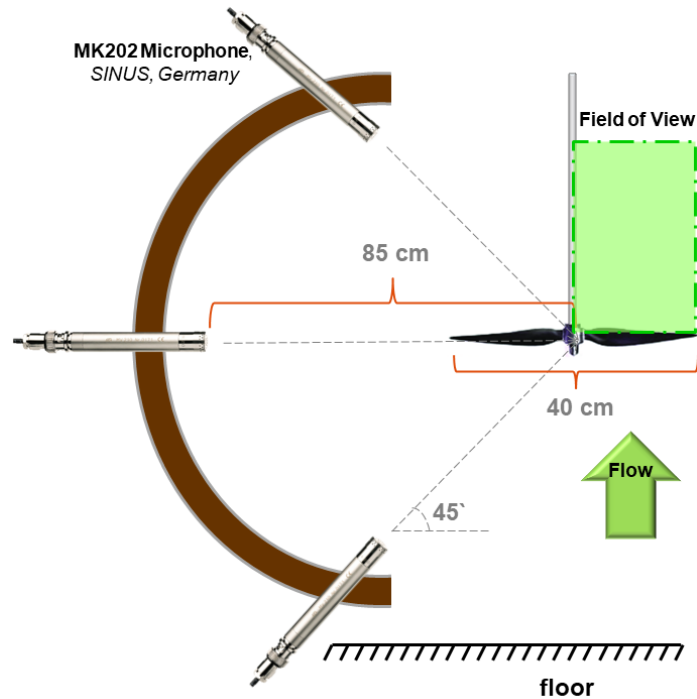


Figure 5. Schematic of the experimental arrangement inside the anechoic chamber. Three MK202 microphones (SINUS, Germany) are positioned on a 0.85 m-radius arc at 0° and $\pm 45^\circ$ relative to the propeller axis to record the radiated sound field. The stereo-PIV field of view (green area) covers a vertical plane behind the rotor, aligned with the laser light sheet.

2.4. Operating Conditions

To facilitate comparisons, all propellers were tested at a constant thrust level of 5 N (approximately the hover thrust for a typical drone motor)—the maximum thrust that the weakest configuration (the TEF propeller) could sustain before reaching its RPM limit. This approach ensures that each design is evaluated on an equal-thrust basis rather than at equal RPM, so that differences in acoustic output can be directly linked to aerodynamic efficiency and flow structure.

The required rotation speed to achieve 5 N differed by propeller; for example, the baseline propeller produced 5 N at ~ 3100 RPM, whereas the less efficient 3D-printed replica needed ~ 3550 RPM, and the toroidal designs required only ~ 2500 RPM (thanks to their larger disk area). During PIV measurements, the motor was operated at the precise RPM corresponding to 5 N for each propeller (as determined from prior calibration).

At this operating point, phase-locked stereo PIV image sequences were acquired as described above. The combination of thrust, noise, and flow measurements provides a comprehensive dataset to assess how each modification influences the flow field and the resulting noise.

3. Results and Discussion

3.1. Comparison at Constant Thrust

Figure 6 compares all propeller configurations at a fixed thrust of 5 N, the operating point used for the stereo-PIV measurements. This condition enables a direct evaluation of the aerodynamic and acoustic efficiency, as the rotational speed (RPM) and corresponding noise level (SPL) required to produce the same thrust reflect the propeller's overall performance.

The required RPM for each configuration was determined by gradually increasing the rotational speed until the measured thrust reached 5 N. Among the tested designs, the **toroidal propellers** achieved this thrust at notably lower RPM than conventional blades, which directly translates into reduced acoustic emission, since rotor sound levels scale with rotational frequency/tip speed (e.g., blade-passing tones at $f_{\text{BPF}} = N_b \Omega / 2\pi$ and broadband components tied to convective velocity); lowering RPM therefore reduces amplitudes and shifts energy to lower frequencies (Candeloro et al., 2022; Zawodny et al., 2016).

In contrast, the **3D-printed replica**, **TES**, and **asymmetric** propellers exhibited greater aerodynamic losses—due to surface finish and departures from the baseline trailing-edge geometry—and therefore required higher RPM to reach 5 N; the resulting increase in tip speed and wake turbulence elevated broadband noise relative to the commercial T-Motor propeller. The **TEF** configuration, affected by its non-conformal microfiber application, developed a pronounced protrusion along the trailing edge that altered the local flow geometry and disrupted the boundary layer. As a result, this configuration exhibited the poorest aerodynamic efficiency, reaching 5 N thrust only at approximately 5200 RPM.

While this constant-thrust comparison provides a clear measure of aerodynamic–acoustic trade-offs, it represents only one aspect of overall propeller performance. Further analysis—such as wake topology, vortex coherence, and turbulence levels obtained from PIV—is necessary to fully interpret the origins of the observed noise differences.

3.2. Baseline vs. 3D-Printed Propeller

We first examine the flow behind the baseline carbon-fiber propeller and its 3D-printed replica. Figure 7 compares the instantaneous and phase-averaged mean velocity fields for these two configurations, both operated at a thrust level of 5 N. The upper row (Figs. 7a,b) shows the instantaneous flow fields, while the lower row (Figs. 7c,d) presents the corresponding phase-averaged mean fields.

The baseline T-Motor propeller (Figs. 7a,c) generates a pair of strong, coherent tip vortices that persist several diameters downstream. These vortices appear as concentrated swirling velocity regions just outside the slipstream core. The phase-averaged mean flow exhibits a narrow, symmetric wake with a well-defined velocity deficit and clearly traceable helical vortex paths.

In contrast, the 3D-printed replica (Figs. 7b,d) produces tip vortices that are noticeably weaker and more diffuse than those of the commercial T-Motor propeller. The instantaneous PIV fields reveal that these vortices decay much sooner, leading to a broader and less organized wake. This more rapid vortex breakdown suggests reduced coherence in periodic blade–vortex interactions,

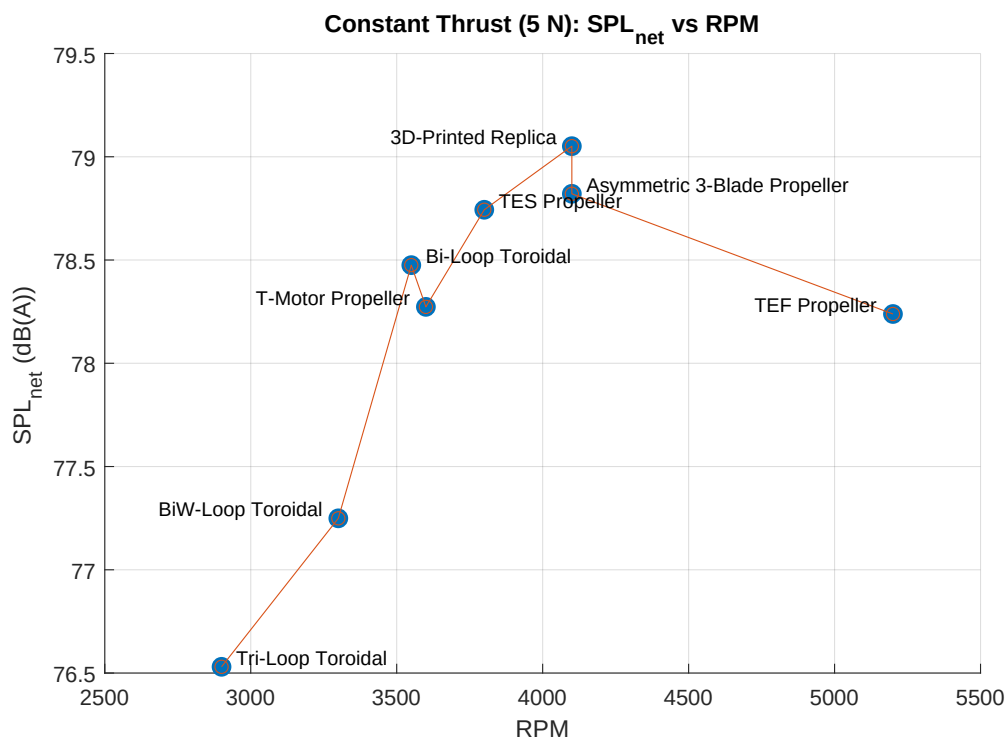


Figure 6. Net A-weighted SPL as a function of RPM at a constant thrust of 5 N. Toroidal designs achieved the target thrust at lower rotational speeds, resulting in reduced noise relative to the T-Motor reference, whereas modified conventional geometries required higher RPM and produced elevated SPL.

which diminishes tonal noise while enhancing broadband noise content, consistent with previous observations linking turbulent wake diffusion to increased broadband emissions. The turbulence intensity (not shown) is also higher, indicating stronger small-scale velocity fluctuations in the printed blade's wake. These effects arise primarily from the 3D-printed propeller's slightly rougher surface finish and minor geometric deviations, both of which promote earlier boundary-layer transition and accelerate vortex destabilization.

Acoustically, the 3D-printed propeller generated a slightly lower overall sound-pressure level (SPL) than the smooth baseline propeller when running at the same rotational speed, owing to its reduced aerodynamic loading. However, it produced relatively stronger high-frequency broadband noise (above about 8 kHz), consistent with the observed increase in small-scale turbulence and earlier vortex breakdown. This demonstrates how surface quality can influence the acoustic spectrum: a rougher blade can shift part of the noise energy toward less audible high-frequency ranges, while slightly reducing tonal components at the cost of aerodynamic efficiency.

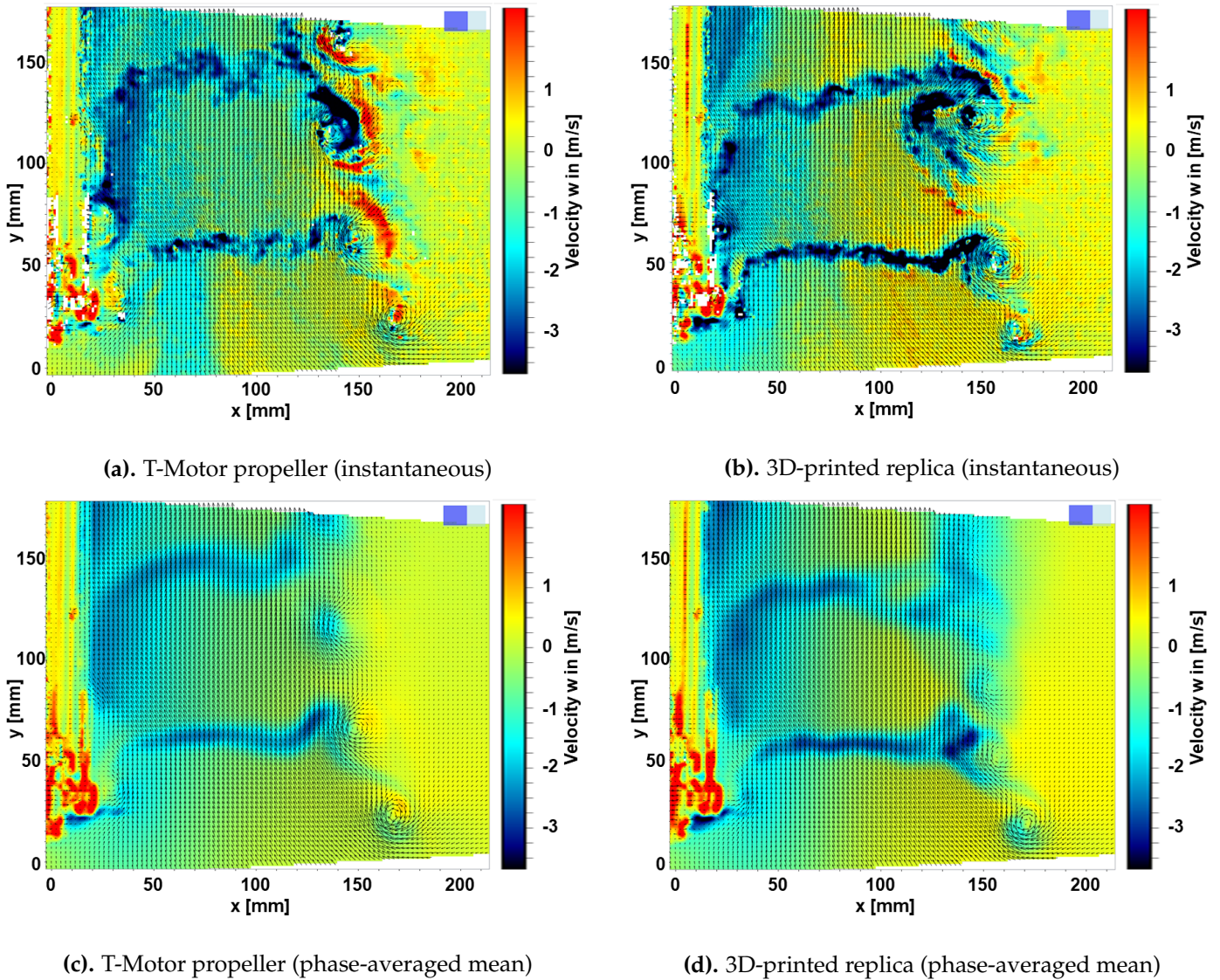


Figure 7. Stereo-PIV velocity fields (flow from bottom to top) at 5 N thrust for (a,c) the baseline T-Motor propeller (3090 RPM) and (b,d) the 3D-printed replica (3540 RPM). The upper row shows instantaneous velocity fields highlighting tip vortex formation, while the lower row presents the phase-average of the velocity field, obtained by averaging all PIV realizations acquired at the same rotor phase angle. The baseline wake exhibits coherent tip vortices and a focused, symmetric jet, whereas the 3D-printed propeller's wake is broader, more turbulent, and shows earlier vortex breakdown.

3.3. Trailing-Edge Modifications (TES & TEF)

Two passive trailing-edge treatments were tested on the baseline geometry to target trailing-edge noise sources. The TES propeller (with serrations) showed only subtle changes in the flow. PIV revealed that the serrated trailing edge introduced fine-scale disturbances along the blade's wake. The tip vortices were slightly more diffuse compared to the baseline, and the shear layer around the wake exhibited earlier mixing. These effects were relatively small, consistent with the modest noise reduction observed: at equal thrust, the TES propeller required $\sim 5\%$ higher RPM than the baseline (due to a slight lift penalty), yet its overall SPL was comparable or slightly lower. The instantaneous flow field for TES (Fig. 8a) appears slightly "ruffled" near the wake edges, indicative

of serration-induced disturbances.

In contrast, the TEF propeller (with a flocked microfiber trailing edge) displayed a dramatically altered flow in a detrimental way. Instead of smoothing the wake, the 0.5 cm fibers effectively formed a blunt trailing-edge ridge. The PIV field (Fig. 8b) shows highly unsteady, separated flow: coherent tip vortices are largely absent, and the slipstream is much wider with a slower jet core. This implies a severe loss of propulsive efficiency, corroborated by thrust data (TEF produced only about 6.6 N at 6000 RPM, versus ~ 14 – 15 N for the baseline). Acoustically, the poorly attached flow led to increased low-frequency broadband noise and the disappearance of distinct tonal peaks. Overall, these results highlight that aerodynamic compatibility is critical for trailing-edge add-ons; poorly implemented compliant treatments can trigger separation and degrade both performance and noise.

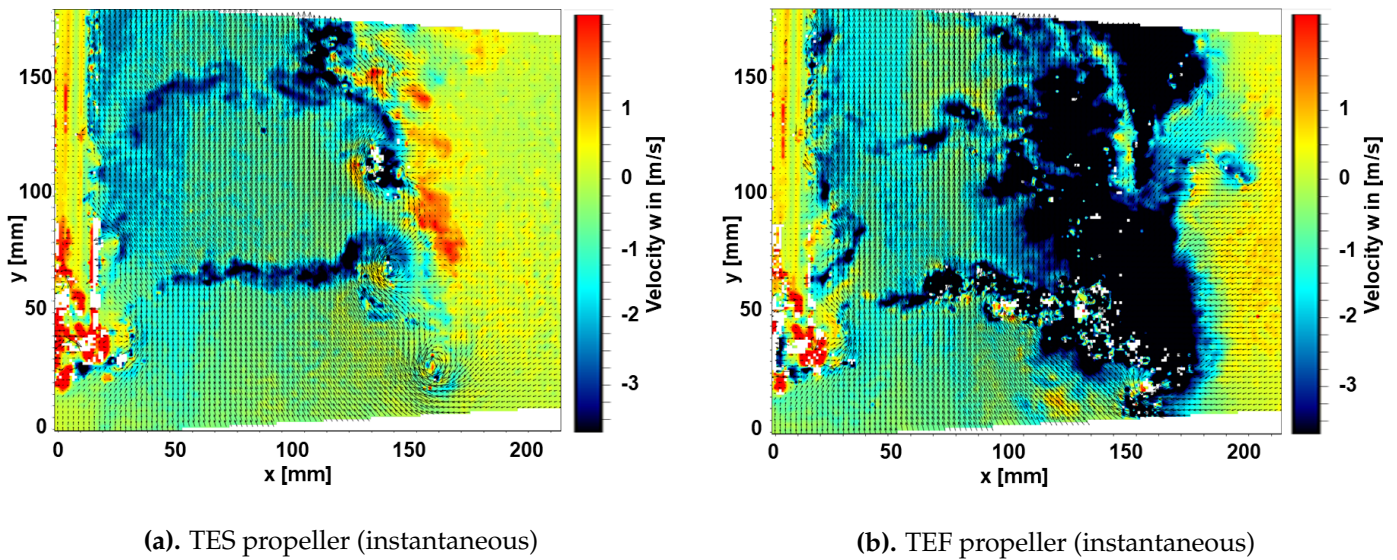


Figure 8. Instantaneous stereo-PIV visualizations at 5 N thrust: (a) trailing-edge serrated (TES) propeller showing slightly broadened tip vortices and mild wake mixing; (b) trailing-edge flocked (TEF) propeller showing highly disorganized wake with premature separation and no coherent tip vortices.

3.4. Asymmetric 3-Blade Propeller

The asymmetric three-blade propeller consists of two large blades and one shorter blade, dynamically balanced about the rotation axis to maintain its center of mass. It was operated at 3240 RPM to generate a constant thrust of 5 N. Stereo-PIV measurements (Fig. 10) were conducted in two separate acquisition shots at different rotor phases. Each shot includes instantaneous velocity fields (top row), phase-averaged mean velocity fields (middle row), and turbulence-intensity maps (bottom row), enabling detailed assessment of the asymmetric wake behavior.

In the instantaneous velocity fields, shown in Figs. 10(a,b), the wake asymmetry is clearly visible. Two strong tip vortices are shed from the larger blades, whereas the smaller blade produces a weaker, less coherent vortex that often dissipates quickly. Shot 1 captures a strong vortex associated with a large blade, while Shot 2 corresponds to a different rotor phase, showing a shifted vortex pattern.

The phase-averaged mean velocity fields, shown in Figs. 10(c,d) reveal a skewed overall jet with

two dominant momentum-deficit regions corresponding to the large blades and one weaker region linked to the small blade. Unlike a conventional symmetric three-blade propeller, the wake lacks uniformity and symmetry about the axis.

The turbulence-intensity maps, visible in Figs. 10(e,f) highlight regions of elevated velocity fluctuations around the strong tip vortices of the larger blades, while the smaller blade's wake exhibits lower turbulence levels. The two measurement shots differ slightly due to nonuniform blade spacing and the asynchronous triggering of the PIV system, which captured different blade passages.

Acoustically, this asymmetric configuration reduced the prominence of the dominant blade-passing tones. The fundamental frequency at 87.5 Hz (one per revolution) became more distinct than the second harmonic at 175 Hz (two per revolution), effectively lowering the perceived pitch. Overall SPL was slightly lower than that of the baseline propeller at equal thrust, and the noise spectrum became more broadband and less tonal (see the 5250 RPM example in Fig. 9). Although its maximum thrust capability was about 30 % lower than the baseline, this design outperformed the TEF and 3D-printed propellers in efficiency and noise reduction (see Figs. 6). The redistribution of aerodynamic loading helps scatter acoustic energy over a broader frequency range, thereby mitigating tonal peaks while maintaining acceptable thrust performance.

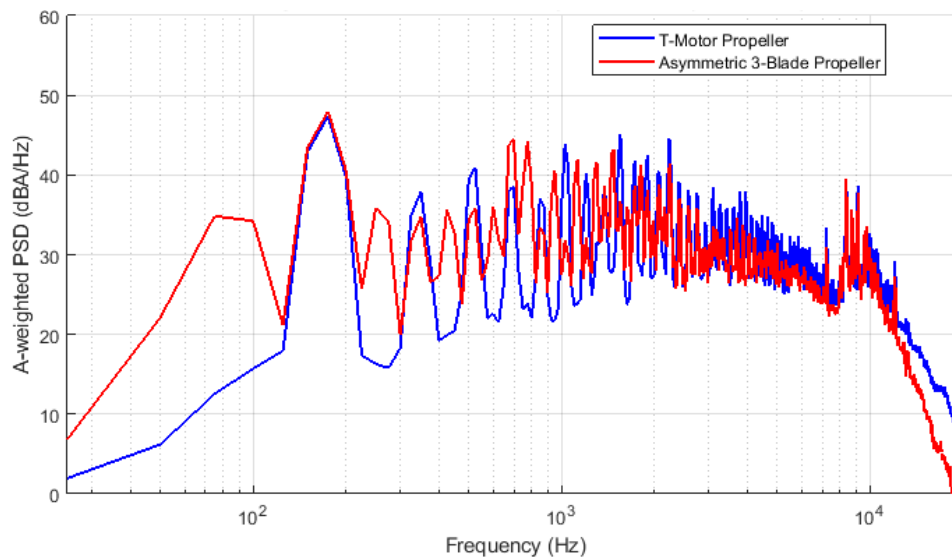
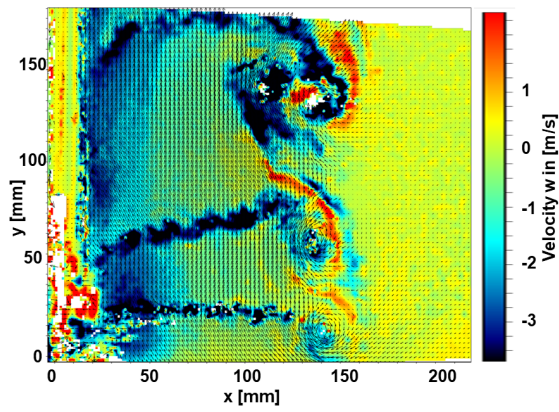
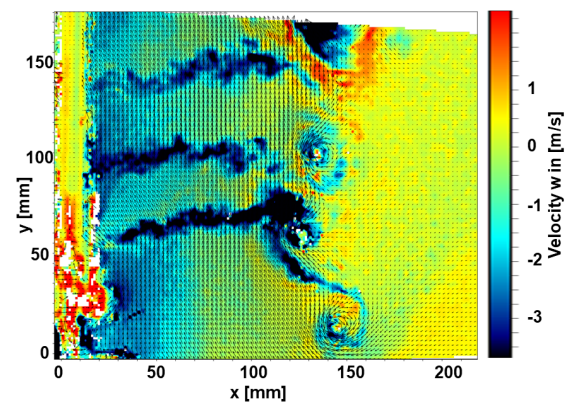


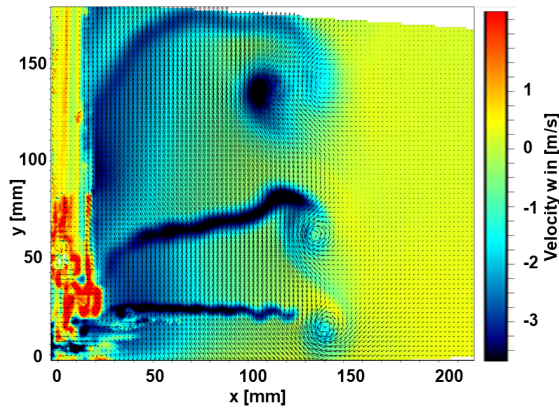
Figure 9. A-weighted PSD at 5250 RPM comparing the T-Motor propeller (blue) and the asymmetric 3-blade propeller (red). A clear tone at the one-per-revolution frequency (100 Hz) is visible in the asymmetric case, while the BPF tone is reduced. Broadband energy is more evenly distributed.



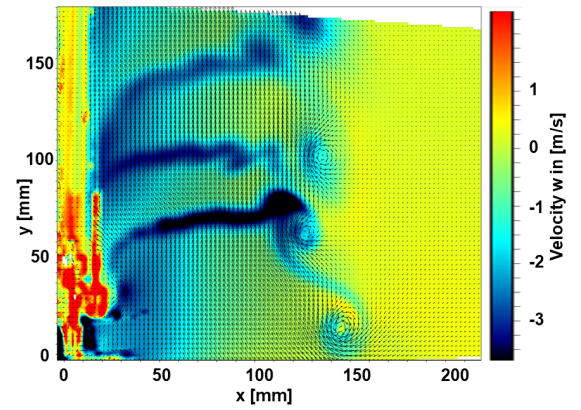
(a). Shot 1 – Instantaneous



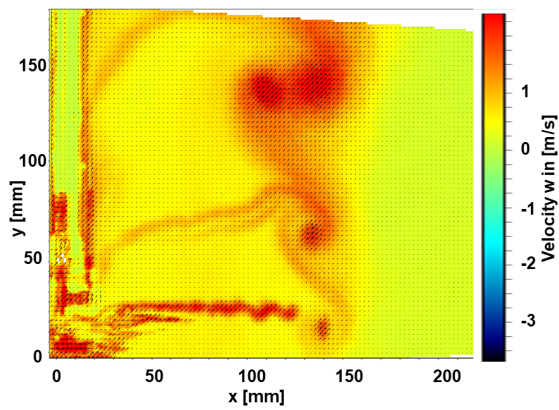
(b). Shot 2 – Instantaneous



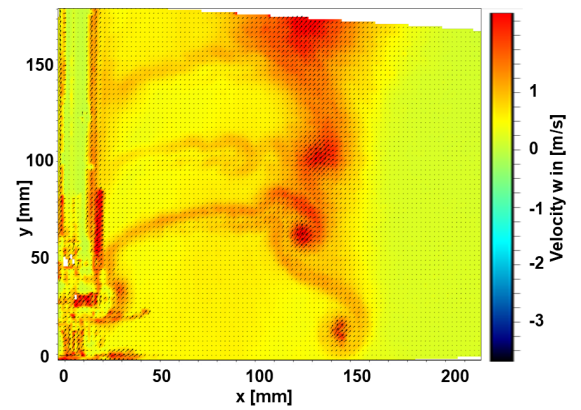
(c). Shot 1 – Mean velocity



(d). Shot 2 – Mean velocity



(e). Shot 1 – StdDev

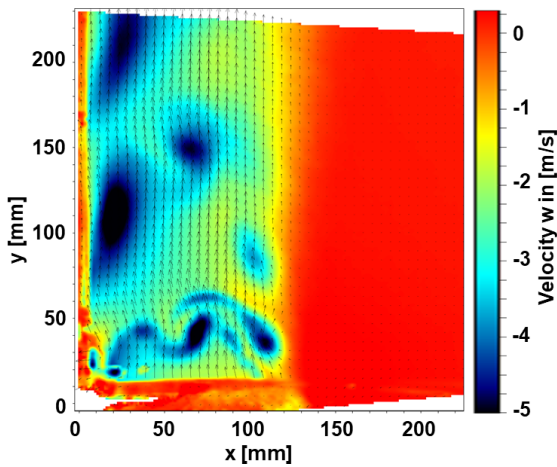


(f). Shot 2 – StdDev

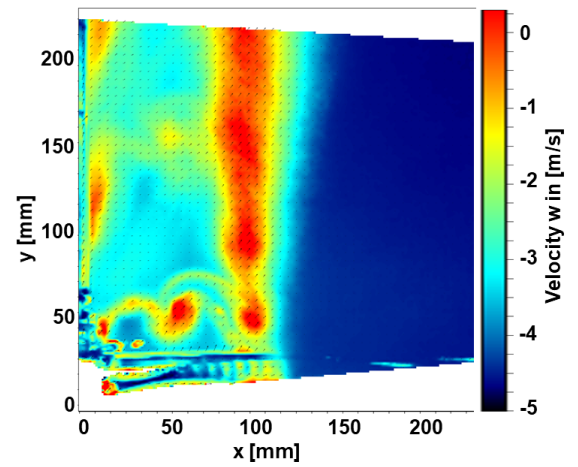
Figure 10. Stereo-PIV results for the asymmetric 3-blade propeller operating at 3240 RPM and 5 N thrust. Two shots (left and right columns) correspond to different rotor phases. Top row: instantaneous velocity fields; middle row: mean velocity; bottom row: turbulence intensity (velocity standard deviation). Two strong tip vortices from the longer blades are consistently visible, whereas the smaller blade produces a weaker or absent vortex.

3.5. Toroidal Propellers

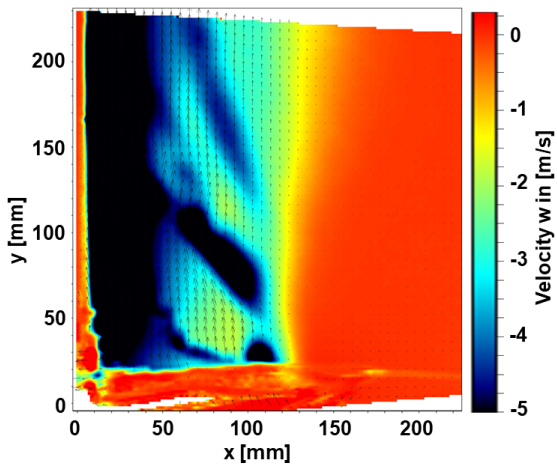
Toroidal propeller designs aim to eliminate tip vortices by connecting the blade tips into continuous loops. In theory, this geometry reduces tip vortex shedding and distributes circulation more evenly along the span. We evaluated two 35 cm outer-diameter toroidal prototypes: a bi-loop and a tri-loop configuration. During initial testing at a fixed thrust of 5 N, the tri-loop toroidal propeller reached the target performance at approximately 2850 RPM, while the bi-loop required around 3300 RPM—both operating at lower or comparable speeds than the baseline two-blade configuration. This reduction in RPM is attributed to the increased disk area and more uniform lift distribution inherent to the toroidal designs. This reduction in required RPM, combined with the suppression of tip vortices, translated to a measurable noise benefit – both toroidal props were about 2 dB quieter in overall SPL compared to the baseline (as shown earlier in Fig. 6).



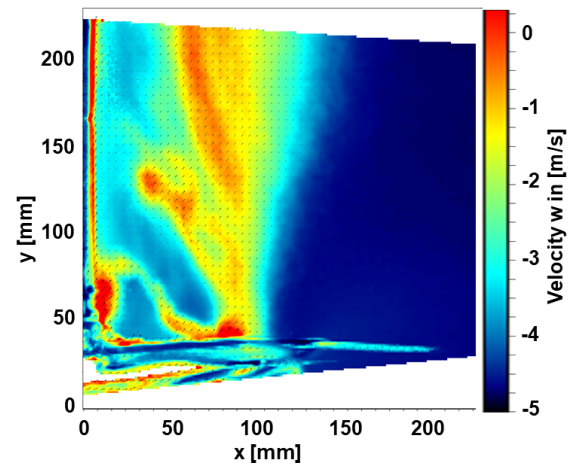
(a). Tri-loop: phase-averaged mean velocity.



(b). Tri-loop: standard deviation velocity.



(c). Bi-loop: phase-averaged mean velocity.



(d). Bi-loop: standard deviation velocity.

Figure 11. Stereo-PIV results for toroidal propellers at 5 N thrust. Both designs suppress distinct tip-vortex cores by redistributing vorticity around the loop.

Figure 11 presents the stereo-PIV measurements in a diametral plane of the wake for the toroidal propellers. In all subplots, arrows show the *in-plane* velocity components (u, v) (radial–axial within the measurement plane), while the color encodes the *out-of-plane* component w (spanwise/azimuthal

with respect to this plane). Subplots (a,b) correspond to the tri-loop design and (c,d) to the bi-loop design. Panels (a) and (c) display the time-mean of w , $\bar{w}(x, y)$, and panels (b) and (d) show the corresponding standard deviation, $\sigma_w(x, y)$.

These results reveal clear differences in both the swirl content (out-of-plane motion) and the in-plane jet collimation. For the tri-loop (Fig. 11a,b), the mean w field is comparatively localized and the fluctuation levels σ_w are mainly confined to a narrow shear layer, while the (u, v) vectors remain well aligned with the axis, indicating a more collimated, axial wake with limited radial spread. In contrast, the bi-loop (Fig. 11c,d) exhibits a broader distribution of mean w and a more extensive footprint of σ_w , together with in-plane vectors that splay outward earlier—evidence of faster wake diffusion and reduced axial coherence. Notably, neither toroidal propeller shows the concentrated helical tip vortices characteristic of conventional two-blade wakes (see Section 3.2). Instead, vorticity is distributed around the loop, and the wake appears as a ring-like shear layer rather than discrete tip-vortex filaments. This redistribution of circulation is consistent with reduced blade–vortex interaction and helps explain the observed noise benefits. Overall, the tri-loop’s lower and more localized w together with a more axially directed (u, v) field point to a more coherent, jet-like wake, whereas the bi-loop spreads momentum more rapidly and loses organization sooner downstream.

3.6. Conclusions

This study combined stereoscopic PIV in a diametral plane with co-located thrust and acoustic measurements to quantify how geometry-driven wake changes map onto perceived noise for drone-scale propellers in hover at a fixed thrust of 5 N. The PIV visualization explicitly resolves the in-plane velocity and the out-of-plane component, enabling a separation of axial jet collimation from swirl and fluctuation content. Equal-thrust normalization allowed a fair comparison of required RPM and SPL across designs (Fig. 6), while the flow fields clarified the mechanisms behind those acoustic trends. Nevertheless, it is important to note that the effective aerodynamic surface area differs between designs and should be considered when interpreting these comparisons (see 1).

Propeller geometry	Approx. area [cm ²]
Two-blade (e.g., T-Motor)	~100
Asymmetric three-blade	~125
Bi-loop toroidal	~270
Tri-loop toroidal	~300

Table 1. Approximate effective aerodynamic area for the tested propeller geometries, used to contextualize equal-thrust comparisons in the text.

Baseline vs. manufactured variants. The carbon-fiber baseline exhibited a narrow, symmetric wake with coherent tip vortices, whereas the high-fidelity 3D-printed replica produced weaker, earlier-breaking vortices and a broader wake (Fig. 7). Acoustically, the printed blade showed slightly lower overall SPL at the same RPM but stronger high-frequency broadband content, consistent with increased small-scale turbulence from surface roughness and minor geometric deviations.

Taken together, these results underscore the role of a smooth surface finish and a sharp, well-defined trailing edge in maintaining lift and wake coherence.

Trailing-edge treatments. Serrations (TES) introduced mild wake ruffling and slightly diffused tip vortices with only modest acoustic benefit; at equal thrust the RPM penalty was small and overall SPL remained comparable to the baseline (Fig. 8). In contrast, the flocked trailing edge (TEF) induced separated, highly unsteady flow, suppressing coherent vortices but at a severe efficiency cost and with increased low-frequency broadband noise. This underscores the need for aerodynamic compatibility of compliant or porous add-ons.

Asymmetric three-blade. The asymmetric rotor redistributed aerodynamic loading, yielding two strong and one weak tip vortex, a skewed mean jet, and spatially localized turbulence around the stronger vortices (Fig. 10). Acoustically, it reduced the prominence of blade-passing harmonics and lowered overall SPL slightly relative to the baseline at 5 N, albeit with a reduced maximum thrust capability. This configuration is promising when tonal mitigation is prioritized and thrust margin is available.

Toroidal (closed-loop) geometries. The toroidal designs achieved 5 N at lower or comparable RPM than conventional blades and were $\sim 2\text{--}3$ dB quieter overall (Fig. 6). PIV shows that both toroidal props suppress distinct tip-vortex cores, replacing them with a ring-like shear layer and a more distributed circulation (Fig. 11). Among them, the tri-loop exhibited a more collimated in-plane jet with a localized mean w and fluctuation field σ_w , indicative of a coherent wake that remains axial farther downstream. The bi-loop displayed broader $\overline{w}$ and more extensive σ_w , and its in-plane vectors splayed outward earlier—evidence of faster wake diffusion and reduced axial coherence. These flow features align with the measured noise differences and point to the tri-loop as the more promising low-noise toroidal variant at equal thrust.

Design implications. (i) Maintaining surface quality and gentle wake manipulation (e.g., mild serrations) can reduce tonal content without large thrust penalties; aggressive or non-conformal treatments (e.g., thick flocking) degrade both efficiency and noise. (ii) Intentional asymmetry can de-emphasize discrete tones but trades off maximum thrust. (iii) Closed-loop (toroidal) architectures effectively eliminate free tip vortices; within this class, tri-loop geometries appear to best preserve a focused, low-fluctuation wake while lowering required RPM and SPL.

Limitations and outlook. The present conclusions pertain to hover, a single measurement plane, and phase-averaged statistics with w reconstructed at slightly higher uncertainty than (u, v) . Future work will extend to forward flight and transient maneuvers, employ phase-locked or volumetric time-resolved PIV to quantify three-dimensional vortex dynamics, and couple these data with array-based acoustics and predictive models. On the design side, systematic parameter sweeps of toroidal geometry (loop count, thickness, camber) and careful combinations with gentle trailing-edge treatments may yield further noise reductions without compromising thrust.

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