

Phase-locked PIV measurements of an accelerating propeller blade at low Reynolds numbers

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ABSTRACT

This study investigates the transient aerodynamic response of an accelerating small-scale propeller for unmanned aerial vehicles, operating at low Reynolds numbers ($10^4 - 10^5$). In this flow regime, the flow over the blade can have laminar separation and vary between being reattached and staying separated at different rotational speeds. Between these two states, the flow response to rapid changes in the rotational speed is still poorly understood, as most studies focused on 2D airfoils, not entire propellers. Experiments were conducted in a low-speed wind tunnel using the rotor blades of a commercially available 10-inch propeller. The pitch of the blades was increased by 10° to mimic higher pitch configurations or the flight envelope of a variable pitch rotor. The propeller disk was placed normal to the oncoming flow, and open-loop step responses of the speed control signal were carried out between rotational speeds where the flow was attached or separated. The rotor response was characterized with thrust load cell and phase-locked particle image velocimetry (PIV) measurements. Data were gathered in quasi-steady conditions at fixed rotational speeds and during the transient acceleration. The thrust measurements show hysteresis, with a maximum difference in the generated thrust of up to 10 % during the moment of strongest acceleration. As a byproduct of the required PIV pre-processing, information about the structural dynamics was recovered, including the out-of-plane deflection and additional twist due to blade loading. While a slight hysteresis is present in accelerating conditions, it seems too small to affect the generated thrust. Vertical velocity profiles extracted over the blade show no hysteresis in the flow field, at least within the resolution of the current PIV setup, even after extensive pre-processing. To further quantify differences, we analyze the airfoil wake through a proper-orthogonal decomposition and compare the leading mode in quasi-steady and unsteady conditions. Results show differences in the wake shortly after the moment of the biggest differences in the thrust coefficient, indicating that changes near the surface of the blade are advected downstream with a small delay.

1. Introduction

Over the recent years, the interest in low-Reynolds-number multi-rotor unmanned aerial vehicles (UAVs) has spiked since they can be used in a large range of applications, ranging from agriculture to environmental monitoring (Hassanalian & Abdelkefi, 2017). The aerodynamics of these vehicles are complex since a laminar separation bubble (LSB) can form over the wing surface due to the low Reynolds number. LSBs are well known to cause a drop in performance and have been mostly investigated for 2D airfoils (Lissaman, 1983; Boutilier & Yarusevych, 2012), but recent investigations also confirmed LSBs to occur for UAV propellers (Grande et al., 2021; Li et al., 2024) by using surface flow visualization, particle image velocimetry (PIV), and pressure sensitive paint. Commonly, the UAVs used fixed pitch propellers, but recently, variable pitch propellers have gained increased attention as they have increased control bandwidth (Cutler & How, 2015) and can be more efficient (Sheng & Sun, 2016).

Even at high pitch angles, it can be desirable to perform changes in the rotational speed to perform agile maneuvers. Yet, changes in the rotational speed have rarely been explored in the literature. Asper & Sirohi (2023) investigated an accelerating rotor with a diameter of 1.016 m at different pitch angles using blade element momentum theory (BEMT; Leishman, 2016) and tabulated data from Reynolds-Averaged Navier-Stokes simulations. They found the thrust magnitude of their model to be consistently lower than that measured in experiments. For fixed pitch propellers, Sekula & Russell (2022) explored different wake and inflow models and found discrepancies with experimental data in both the mean and the vibratory thrust loads. The blade-level aerodynamics likewise used tabulated data based on XFOIL (Drela & Giles, 1987) and BEMT. A recent numerical investigation by Grava et al. (2026) used a meshless vortex particle method to analyze rotor speed changes at low Reynolds numbers with different acceleration rates. They found an increased thrust during the acceleration due to a lag in the inflow, but, as in the other investigations before, the authors employed fixed values for the aerodynamic coefficients.

However, the aerodynamics might not be quasi-steady when an LSB is present on the airfoil. Acceleration effects were investigated by Ellsworth & Muller (1991), who found that the position of the LSB shifts opposite to quasi-steady trends. Likewise, accelerations from rest (Dierl et al., 2024) showed that under strong acceleration, the LSB properties change for multiple flow-through times even after the acceleration has ceased. Yet, these investigations considered relatively strong accelerations which are typically not reached by UAV propellers during flight. Quasi-steady changes between attached and separated LSB were recently investigated (Toppings & Yarusevych, 2024), and the authors found that the LSB dynamics can introduce significant hysteresis in the lift. Moreover, they found that the hysteresis varies strongly between 2D airfoils and 3D wings. It is currently unknown how these findings translate to propellers at low Reynolds numbers, where the LSB is much flatter than on airfoils (Khedr & Castellani, 2025).

In this work, we investigate an accelerating propeller at low Reynolds numbers by performing open-loop step responses in the control signal between 3000 and 5000 RPM. Since the system response occurs in approximately 0.1 s, surface flow visualization and pressure sensitive paint cannot be employed. Instead, we resort to thrust measurements and phase-locked PIV of different radial propeller sections. A significant challenge is posed by the small chord and the blade reflections which lead to limited spatial resolution near the propeller surface. Instead, we correct for the blade motion to align all data in the blade reference frame and then analyze the wake at the trailing edge with proper orthogonal decomposition (POD; Berkooz et al., 1993) as the shape and size of the vortices can indicate whether an LSB is present or not (Yarusevych et al., 2006; Grande et al., 2021).

2. Facility and Instrumentation

2.1. Propeller test rig and test conditions

The main components of the propeller test rig are depicted in Fig. 1(a). The propeller consists of a blade holder in purple to which the gray propeller blades are fastened with bolts. The propeller blades stem from a commercially available propeller X500 V2 1045, which is the default propeller for a Holybro PX4 Development Kit. The blade holder increases the pitch of these blades by 10° with respect to the default configuration to simulate high pitch conditions for variable pitch propellers. The resulting diameter is $D = 310.5$ mm. The propeller is driven by a T-motor AT3520 550KV brushless DC motor, driven by a T-Motor AT75A 2-6S controlled with a hardware pulse width modulation (PWM) signal from a Raspberry Pi 5. The motor speed is measured with a CUI AMT11 incremental encoder with a resolution of 2048 pulses per revolution. The pulses of the encoder are counted over an interval of 2 ms with an Arduino Giga R1 Wifi which gives an effective acquisition frequency of 500 Hz for the rotational speed. Below the encoder sits a FUTEK QMA150 load cell with a resolution of 100 N whose signal is acquired with an MCC 128 DAQ HAT at a frequency of 10 kHz with a resolution of 16 bits.

Measurements were conducted in the W-tunnel at TU Delft, where the propeller was positioned with the disk normal to the oncoming flow. The free-stream velocity was set to 11 m/s. The propeller was characterized in two conditions: quasi-steady and unsteady. For the quasi-steady measurements, the measurements were acquired at constant rotational speeds between 2750 and 5250 RPM with a step size of 250 RPM. For the unsteady measurements, we conducted open-loop step responses in the control signal of the rotational speed between 3000 and 5000 RPM. The 10 to 90 % rise time for this acceleration occurs in approximately 0.1 s. Loads and rotational speed are acquired at each constant rotational speed over 30 s, and for the accelerations by repeating the step responses 500 times.

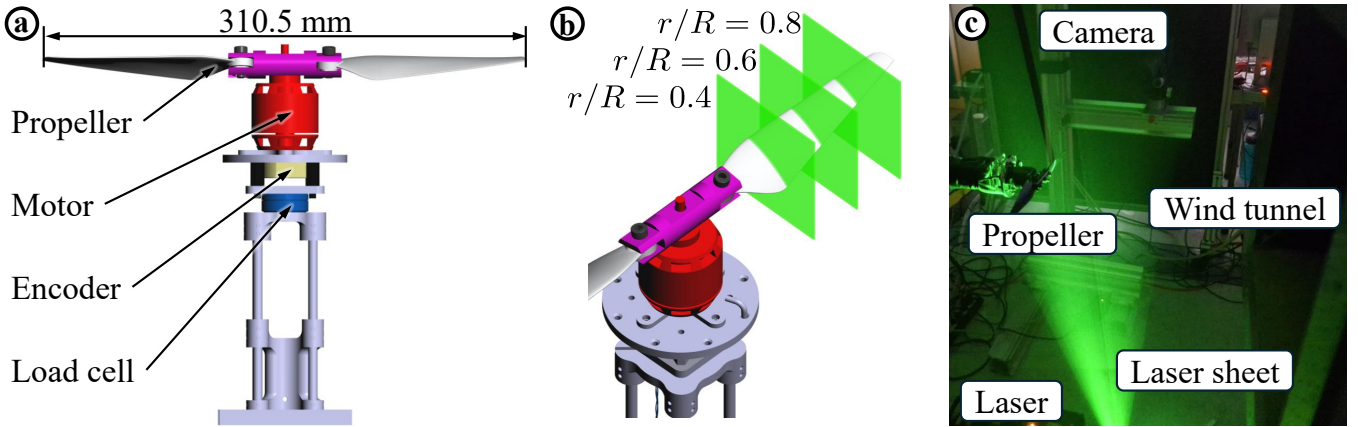


Figure 1. Propeller test rig. (a) Propeller (gray/purple), drive train with the motor (red), optical encoder (yellow), and thrust and torque cell (blue). (b) PIV measurement locations at different spanwise locations. (c) Picture of the planar PIV setup for $r/R = 0.6$.

2.2. Phase-locked PIV setup

Given the high rotational speed and small scales of drone propellers, we used phase-locked PIV to characterize the flow at the local blade scales. The flow was seeded with a SAFEX Twin Fog generator with SAFEX-Inside-Nebelfluid with a water-glycol mixture with a median particle diameter of $1\text{ }\mu\text{m}$. Laser light was provided by a Quantel Evergreen EVG00200 Nd:YAG laser with a maximum energy of 200 mJ per pulse. The beam was expanded with a cylindrical and spherical lens to obtain a laser sheet with a thickness of approximately 1 mm . The laser sheet is positioned at different spanwise locations of $r/R = 0.4, 0.6$, and 0.8 to observe how the local flow behaves at different radial sections. An illustration of these spanwise laser sheet locations is provided in Fig. 1(b), and Fig. 1(c) shows the setup mounted in the wind tunnel with the laser sheet position at $r/R = 0.6$. The associated non-dimensional numbers are summarized in Table 1, where the Reynolds number is computed based on the local chord c and local blade velocity u_{blade} and a_{blade} is the local acceleration. The $10 - 90\%$ rise time is defined as $D = \frac{1}{c} \int_{t=0}^t u_{\text{blade}}(\tau) d\tau$ and corresponds to the number of chord lengths each airfoil section passes.

The droplets were illuminated with a low-speed LaVision Imager sCMOS camera with a resolution of $2560\text{ px} \times 2160\text{ px}$ and a pixel pitch of $6.5\text{ }\mu\text{m}$. The camera was equipped with an AF Micro-

Table 1. Experimental test conditions.

r/R [–]	Re_c [$\times 10^4$]	$ ca_{\text{blade}}/u_{\text{blade}}^2 $ [–]	D_{10-90} [–]
0.4	4.74 ... 7.27	≤ 0.010	75
0.6	5.11 ... 8.18	≤ 0.005	146
0.8	4.74 ... 7.17	≤ 0.003	271

Table 2. Parameters of the PIV system.

r/R	0.4	0.6	0.8
Camera	LaViSion Imager sCMOS		
Pixel size	$6.5 \times 6.5 \mu\text{m}^2$		
Sensor size	$2560 \text{ px} \times 2160 \text{ px}$		
Field of view	$51.8 \times 43.7 \text{ mm}^2$		
Objective	AF Micro-Nikkor 200 mm		
Aperture $f\#$	11		
Magnification	0.32		
Imaging resolution	49.4 px/mm		
Number of samples	200	500	200
Laser pulse separation	12–23 μs	8–15 μs	6–11 μs
Laser source	Quantel Evergreen 200 Nd:YAG		
Max. acquisition frequency	15 Hz		
Laser sheet thickness	1.5 mm		
Acquisition software	DaVis 8.4		
Particle seeding	SAFEX water-glycol droplets, 1 μm		

Nikkor 200 mm, yielding a field of view (FOV) of approximately $51.8 \times 43.7 \text{ mm}^2$. The camera was positioned with an angle of approximately 5° with respect to the laser sheet, as the propeller blade has a winglet that blocks viewing the surface. To have well-focused particles, the camera was equipped with a Scheimpflug mount and was operated with an aperture of $f\# = 11$. Moreover, the fast response mode of the cameras was used to ensure minimum delay times between the received trigger and the captured image. All acquisitions were carried out using DaVis 8.4, and the most important acquisition parameters are summarized in Table 2.

Phase-locking was achieved with the index signal of the encoder, which provides a pulse once per revolution. This pulse is sampled by another Arduino Giga R1 Wifi and fed to the synchronizer of the PIV system. Since camera and laser have a delay between received trigger pulse and captured image, the index signal is offset by approximately 120° with respect to the camera. At constant speed, the additional delay is simply adjusted in the acquisition software and set individually for each constant rotational speed. The resulting jitter of the blade position is discussed in Sec. 3.1.

For the acceleration, there are two additional challenges. First, the acceleration happens within approximately 0.1 s, corresponding to 9 rotor revolutions for these conditions. The camera and laser can have a maximum frequency of 15 Hz and can thus not capture every revolution on every step. Second, the speed changes and a constant delay in the acquisition software is not sufficient since different rotational speeds require different delays. The problem of the frequency was tackled

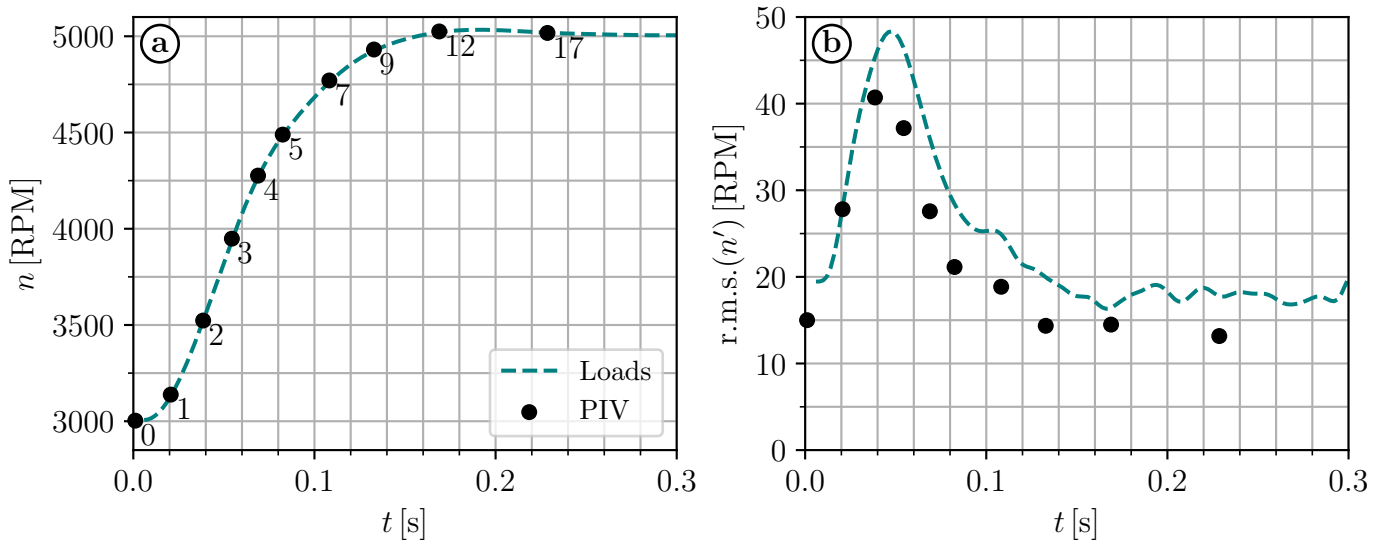


Figure 2. System response in the rotational speed. Mean speed (a) and r.m.s. of fluctuations (b) for the loads measurements (dashed line) and PIV phaselocking (black dots). The annotations of the points in subfigure (a) give the revolutions since the start.

by capturing images with a staggering of 6 revolutions and a different modulus. Initially, images were captured at revolutions 0, 6, 12, ... and steps were repeated multiple times as was done for the loads measurements. Next, revolutions 1, 7, 13, ... were captured and so forth until every revolution since the start was captured. The non-constant trigger delay was handled with the second Arduino by tracking the revolution count since the start and assigning an individual delay to each revolution. This delay was computed from the mean rotational speed response from the load measurements.

The step responses with PIV were repeated until 500 snapshots were available for each phase-locking point at $r/R = 0.6$ and 200 for $r/R = 0.4$ and 0.8 . The quasi-steady measurements used the same rotational speeds as the thrust, and the same number of samples was acquired at each spanwise position. Evidently, this experimental procedure required the system response to be consistent over long periods of time, which is why the initial and final set points of the open-loop steps were controlled with a conservative PID controller. The resulting mean response in the rotational speed n is shown in Fig. 2(a) for both the loads and PIV measurements for $r/R = 0.6$, while Fig. 2(b) shows the r.m.s. values of the rotational speed fluctuations. For technical reasons, the first 5 ms of the load measurements are not available since the DAQ hat has an initialization period. Not all revolutions since the start were acquired to keep the data analysis manageable. Instead, selected revolutions were acquired, which are annotated to each marker of the phase-locking points. It can be seen that the accelerations have strong repeatability with the r.m.s. values never exceeding 50 RPM, corresponding to relative fluctuations of 1.5 %. The other two measurement positions result in similar values for both the mean and r.m.s., which is why they are omitted here.

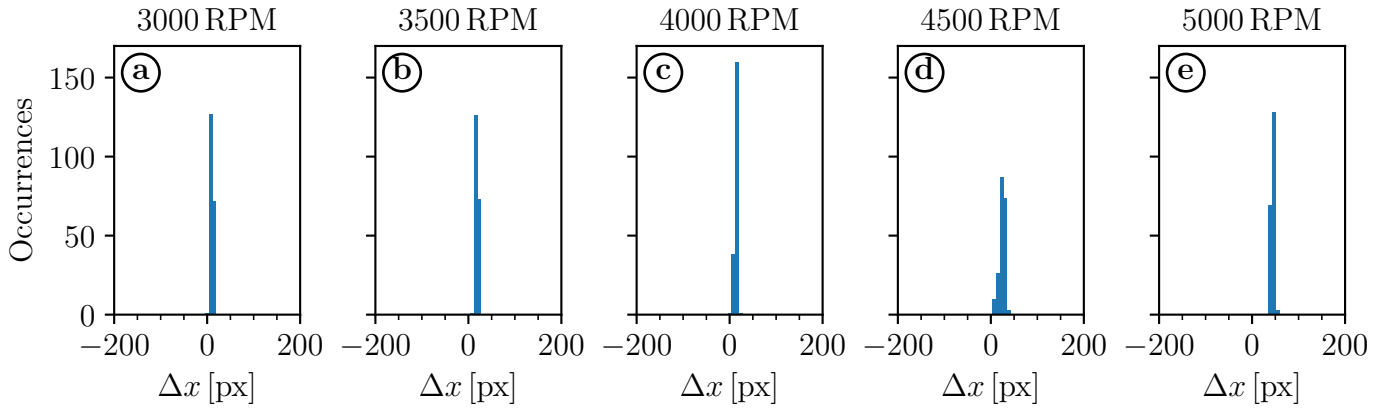


Figure 3. Horizontal displacement Δx of the trailing edge with respect to the reference frame at $r/R = 0.8$ in quasi-steady conditions between 3000 and 5000 RPM.

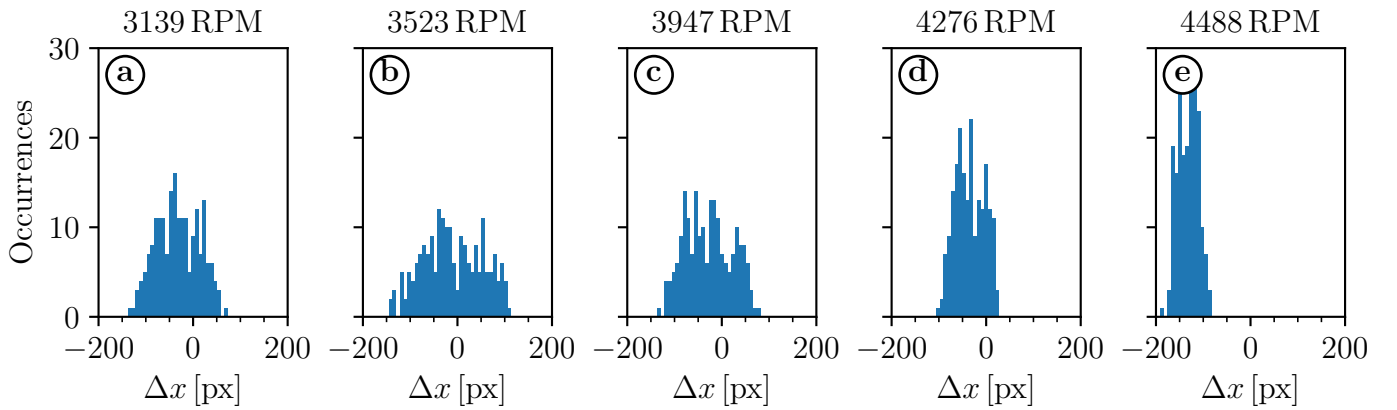


Figure 4. Horizontal displacement Δx of the trailing edge with respect to the reference frame at $r/R = 0.8$ in accelerating conditions for revolutions 1-5 (c.f. Fig 2a). The titles indicate the mean rpm of this ensemble.

3. Results

3.1. PIV processing

Due to the jitter in the blade position, extensive image pre-processing is required. Furthermore, the fast response mode of the camera and the large magnification resulted in poor imaging conditions. First, a pixel-wise minimum is subtracted from each image using a sliding minimum with a window length of 7. This removes the additional fixed pattern noise stemming from the fast response mode, where the reference background image is taken after the frame with the laser. Next, all images are aligned with respect to a representative reference image at 2750 RPM for each span-wise location. To achieve this, the reflection of the trailing edge is localized with morphological opening, closing, and thresholding. A cross-correlation of this trailing edge region is used to find the displacement $(\Delta x, \Delta y)$ of each image with respect to the reference. Here, x is defined in the azimuthal direction of the rotor, while y is defined as the coordinate normal to the rotor disk.

Figures 3(a–e) show the histograms of the horizontal displacement Δx in quasi-steady conditions at different fixed rotational speeds for $r/R = 0.8$. In all cases, the random error due to the jitter of the speed controller is relatively small, and the displacement values show a maximum range of 50 px. They show a maximum bias of approximately 40 px, which mostly stems from the entered accuracies of the delay time in DaVis. These values are still excellent for repeatability since a displacement of 50 px corresponds to an offset of approximately 0.47° at this span.

In comparison, the fluctuations are larger during acceleration, as depicted in Figs. 4(a–e), which show the displacement histograms of revolutions 1-5. These occur during the strongest acceleration (c.f. Fig. 2(a)) and have ranges of up to 300 px as well as more significant biases of approximately 150 px. As before, the jitter is attributed to the speed controller as it is updated with a frequency of 500 Hz, and the command to accelerate therefore carries a jitter of 2 ms, which translates into the blade positions. This is where the fast response mode of the camera was crucial, as the normal mode of the camera has a minimum time delay of 10 ms, resulting in significantly more jitter, while the fast response mode allows minimum delays of 1 ms. The bias in the displacements stems from improper dynamic delay times given to the Arduino. These delay times were already iteratively improved with small adjustments through trial-and-error. Further improving them through iterative acquisition and processing was not deemed reasonable, as the offsets in the angle were small enough for accurate processing, and the time required too large because of the limited wind tunnel time. The histograms of the inboard sections at $r/R = 0.4$ and 0.6 exhibit smaller ranges and biases as the local blade velocity is smaller, but the variations in the angle are comparable, which is why they are not shown here.

Afterward, an ensemble of images was obtained for each rotational speed by discarding images with too small correlation coefficients or too large displacements in either axes. The remaining images were then cropped to a moving reference frame to obtain a pixel-wise mean image of the reflection. This mean image is used to fit the orientation of the local blade section based on a 3D scan of the blade, allowing to accurately locate leading and trailing edge and to quantify the additional twisting of the blade due to loading. Furthermore, it can be used to efficiently mask the shadow region of the laser without having to mask each ensemble of images separately.

The final step is the actual preprocessing. We found standard methods, such as a global minimum subtraction or POD-based removal (Mendez et al., 2017) insufficient to remove the laser flare near the reflection of the blade in the image. Even removing a large number of POD modes did not yield sufficient results, as it affected particle images with high intensity and even led to ghost particles. We suspect that this is because of the jitter of the blade. Even though the variations in the angle are small, the camera image comes from slightly different views of the blade. In combination with the fixed pattern noise, this smears the reflection in the blade-aligned images and requires the removal of too many modes.

Instead, we use a normalization approach, using the mean image from before. Every image is

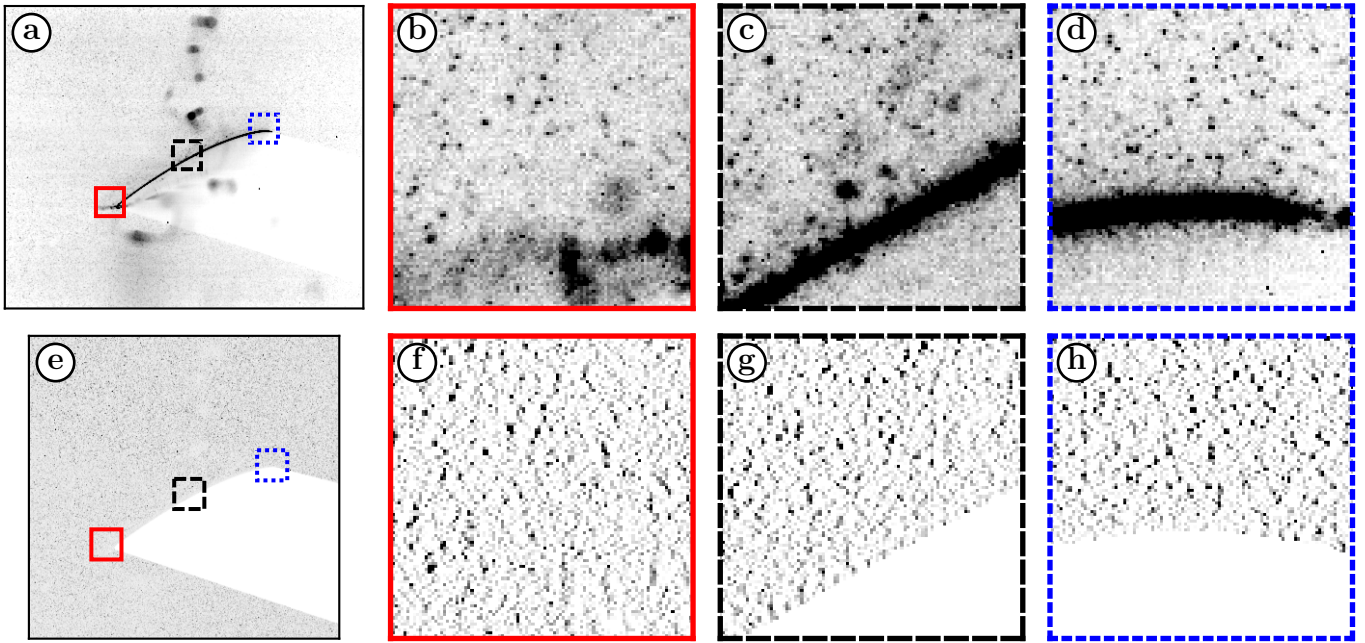


Figure 5. Preprocessing for a representative image at 5000 RPM and $r/R = 0.6$. Full FOV (a), zoom at the trailing edge (b), zoom at the mid-chord (c) and zoom at the leading edge (d). Subfigures (e–h) show the same regions of interest after all preprocessing steps.

divided by the mean and a sliding temporal mean over 7 consecutive images is subtracted from each image. This is a relatively aggressive filter, but it was needed to remove large background reflections of the propeller hub that are visible because of the large depth of field. This is depicted in Fig. 5(a), showing a raw image at 5000 RPM at $r/R = 0.6$, where the propeller hub reflections are the large, dark regions, which form a slightly tilted, vertical column in the center of the image. After the filter, the images are multiplied by the median of the mean image to avoid discretization errors due to small intensities. We choose this single, scalar value to attenuate the laser flare near the surface, which is mostly present at the propeller blade as both chord and twist of the blade vary along the span, and the large aperture leads to imprints of inboard sections in the images. These issues are depicted in Figs. 5(b–d) which show regions highlighted in Fig. 5(a). The blade reflection is clearly visible as a large continuous area, as are the particles, which are relatively large at 3–4 px. The additional patchy regions, particularly in Figs. (b) and (c) are undesired and stem from reflections along the span, which are imaged because of the large depth of field.

The same images after background removal are depicted in Figs. 5(e)–(h). The large reflections of the propeller hub are removed well, as are the local, patchy regions due to near-surface reflections. However, the aggressive removal also results in only a small number of particle images near the propeller surface, as only the small particles enter the near-wall region. Their intensity is comparable to the remaining flare, which is why we additionally masked the area within 15 px of the wall.

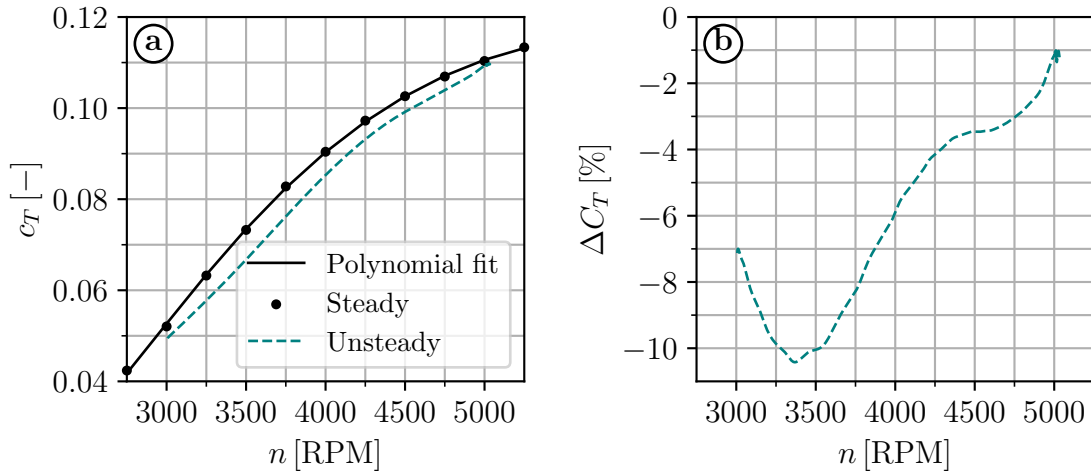


Figure 6. Results of the load measurements. Thrust coefficient as a function of rotational speed in quasi-steady conditions (black) compared to the unsteady case (teal) (a) and relative difference in the thrust coefficient (b).

The pre-processed images were processed with the open-source software PaIRS (Paolillo & Asarita, 2024), which uses a multipass algorithm with window deformation Scarano & Riethmüller (2000). The initial window size was $128 \times 128 \text{ px}^2$ which was reduced to $32 \times 32 \text{ px}^2$ during two passes, keeping an overlap of 75 %. At each iteration, outliers were filtered with a normalized median filter (Westerweel & Scarano, 2005) and replaced by interpolation. The resulting data are an ensemble of velocity fields at each phase-locking point during unsteady and at each constant rotational speed during quasi-steady measurements. Using the results of fitting the blade orientation to the reflection, we align the velocity data in the blade reference frame, correcting for both rotation and displacement. Since this changes the grid points between rotational speeds, we interpolate the data in (x, y) to have data on the same grid.

Each ensemble is then analyzed with different methods. The first is a POD (Berkooz et al., 1993) of the wake using the method of snapshots (Sirovich, 1987), employing the 500 (200) snapshots available at $r/R = 0.6$ (0.4, 0.8). In case of flow separation without reattachment, the local blade should shed large, coherent vortices, while the vortices should be smaller and less coherent for a reattached flow (Yarusevych et al., 2006; Grande et al., 2021). The second analysis compares the mean flow between quasi-steady and unsteady conditions. Since the rotational speeds between the two conditions do not match, we interpolate the quasi-steady measurements in the rotational speed to express them at the same speeds as the unsteady ones. For the further visualizations, we non-dimensionalize the vertical velocity by the blade velocity U_{blade} and the spatial coordinates by the horizontal projection c_x of the chord c .

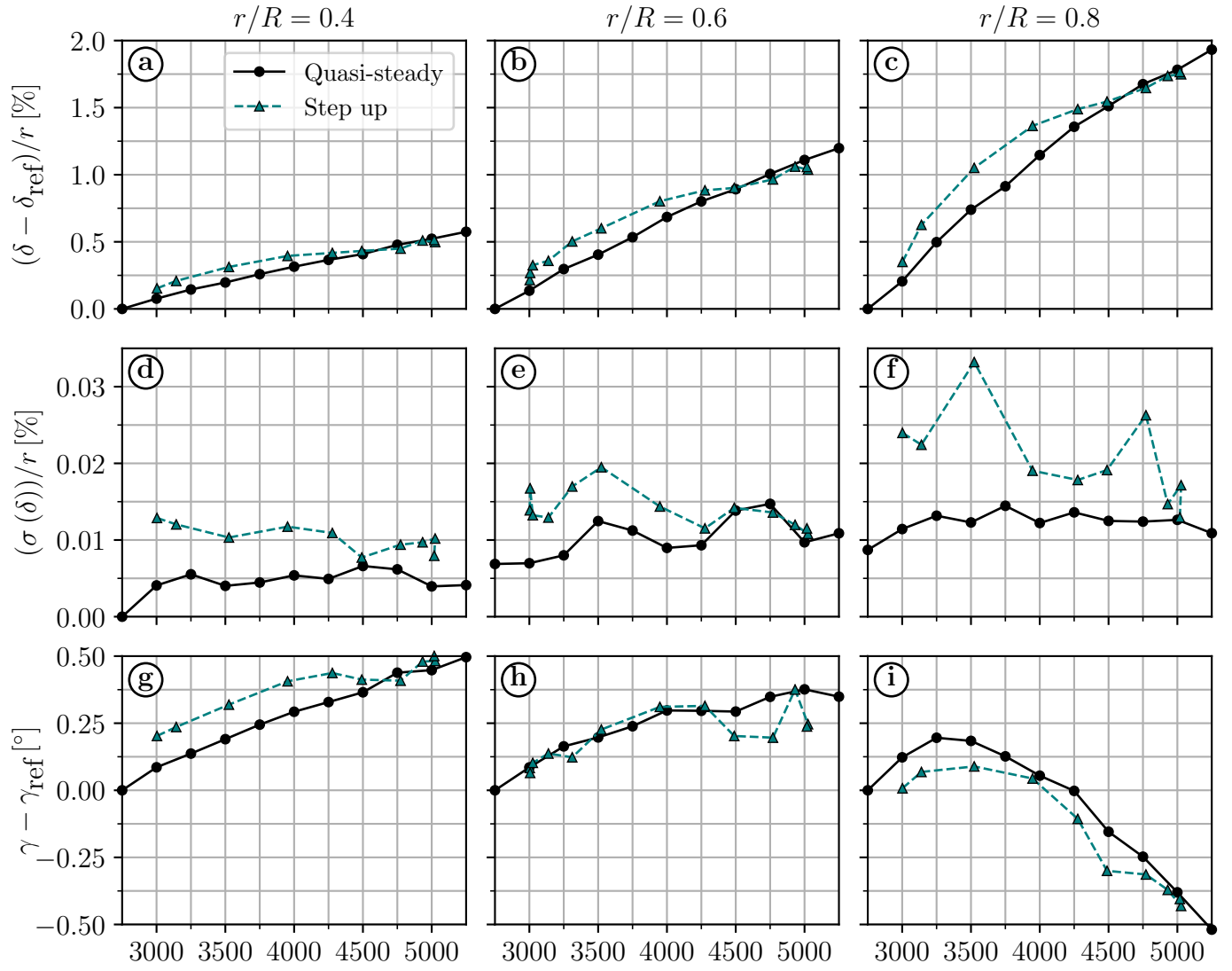


Figure 7. Results of the out-of-plane blade deformation due to aerodynamic loading. Mean vertical displacement δ with respect to the reference at 2750 RPM (a-c), standard deviation of the vertical displacement (d-f), and additional twist γ with respect to the reference (g-i). The columns correspond to different spans according to the titles and the legend in subfigure (a) applies to all subfigures.

3.2. Aerodynamic results

The measurements of the thrust are used to compare quasi-steady and unsteady measurements to check for hysteresis in the thrust. The unsteady data are filtered with a 3rd order Butterworth low-pass filter with a cut-off frequency of 30 Hz for visualization purposes. Furthermore, the thrust data are non-dimensionalized with the thrust coefficient as $c_T = T / (\rho D^4 (n/60)^2)$, where T is the thrust and ρ is the density. Figure 6(a) compares the thrust coefficient for the quasi-conditions with the step up. A hysteresis is clearly visible with a continuously lower thrust coefficient for the accelerating propeller. This trend is opposite to what was previously observed numerically

(Grava et al., 2026) and experimentally (Ratz et al., 2026) for propellers with smaller pitch and little separation. To further quantify the difference, Fig. 6(b) compares the relative difference in the thrust coefficient $\Delta C_T = (C_{T_{\text{steady}}} - C_{T_{\text{unsteady}}})/C_{T_{\text{steady}}}$. We observe a maximum difference of 10.5 % around 3350 RPM, and the differences remain significant until 4250 RPM.

3.3. Aeroelasticity results

A potential cause of the thrust hysteresis is an unsteady additional twist angle of the blade sections due to acceleration. To investigate this, we characterize the elastic response of the rotor using the results from the cross correlation of the trailing edge and fitting of the mean reflection to the local airfoil geometry. To this end, Figs 7(a–c) show the average vertical displacement of the trailing edge δ with respect to the reference displacement at 2750 RPM, normalized by the local radial section. The quasi-steady response (black dots) is a linear function of the rotational speed, and the displacement increases with increasing radius, reaching a maximum displacement of 2 % at $r/R = 0.8$ at 5250 RPM. The unsteady response (blue triangles) is shown in the same figures and only shows small differences. Again, these differences increase with increasing radius, reaching a maximum difference of approximately 0.3 % occurs around 4000 RPM for $r/R = 0.8$. Yet, these differences are relatively small, and comparisons between rigid and flexible blade models showed only small differences for the thrust Russell & Sekula (2017).

The r.m.s. values of the vertical fluctuation $\sigma(\delta')$ in Figs 7(d–f) show that this mean response is consistent since the fluctuation relative to the mean does not exceed 10 % across all cases and all conditions. Moreover, the absolute fluctuations appear almost constant and do not increase with increasing rotational speed. In comparison, the unsteady response shows higher fluctuations, sometimes more than doubling the quasi-steady values. At the moment, it is unclear whether this is caused by higher unsteady loading or because the larger horizontal displacements (c.f. Fig. 4) also affect the accuracy of the vertical displacement.

Lastly, the twist angle can be computed from the fit of the reflection with the airfoil geometry. The additional twist with respect to the reference at 2750 RPM for the different radial sections is depicted in Figs. 7(g–i). At $r/R = 0.4$, the additional twist increases linearly as a function of rotational speed, with a maximum additional twist of 0.5° at 5250 RPM, matching previous observations at smaller pitch angles (Ratz et al., 2026). The unsteady response only shows maximum differences of 0.25° which is relatively small compared to the local twist angle. Further outboard at $r/R = 0.6$, the response does not show the same clear linear trend, but the maximum differences remain of similar magnitude. Finally, at $r/R = 0.8$, the trend reverses, and after initially increasing, the additional twist angle decreases, down to a maximum difference of -0.5° . The difference to the unsteady measurements again has similar magnitudes. While these differences are small, they highlight that comprehensive aeroelastic modeling of UAV rotor blades requires a full spanwise characterization of the blade, and not just individual sections. In the present ex-

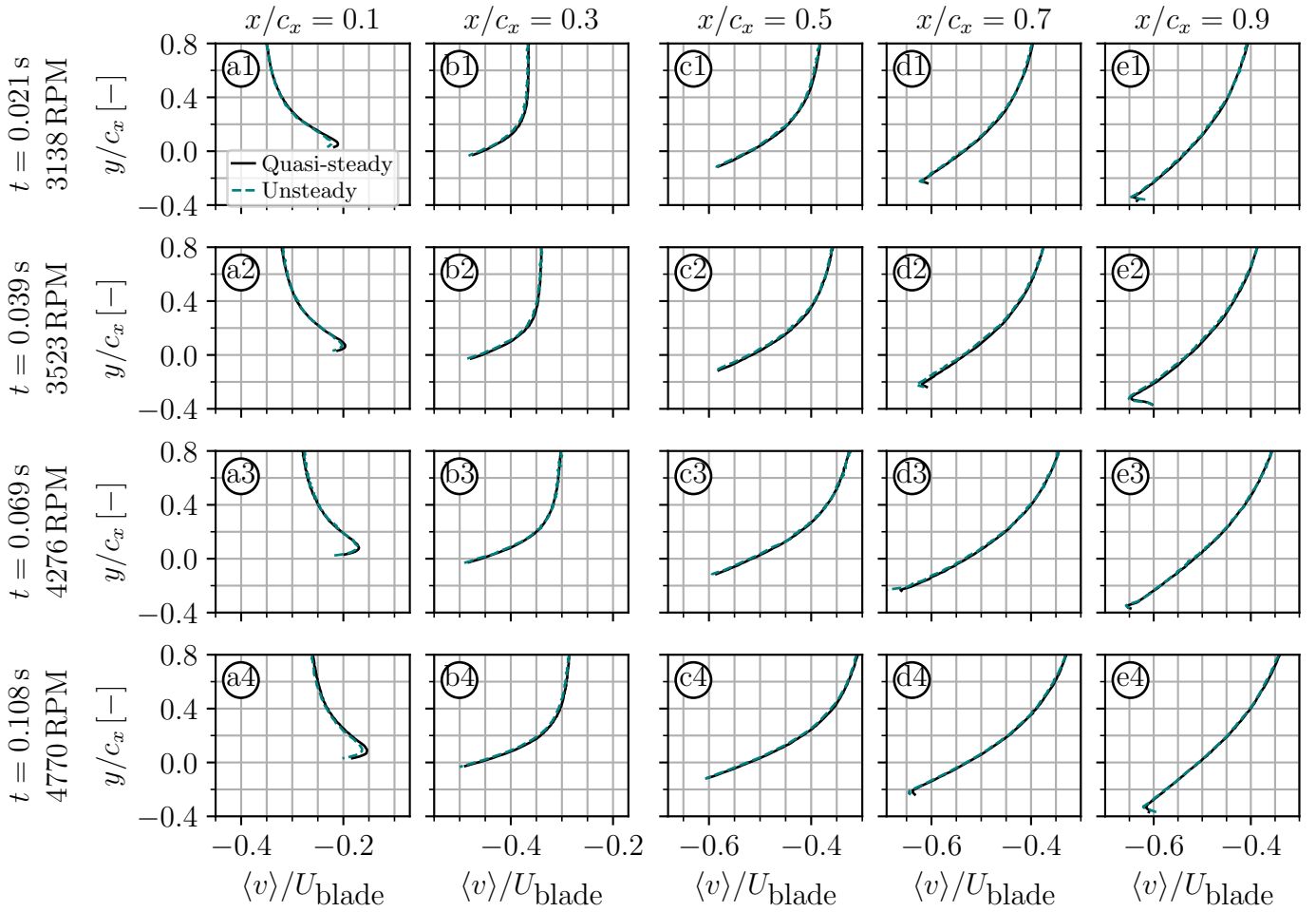


Figure 8. Normalized vertical velocity profiles $\langle v \rangle / U_{\text{blade}}$ for $r/R = 0.6$. The columns indicate different chordwise positions at $x/c_x = 0.1, 0.3, 0.5, 0.7, 0.9$, and the rows correspond to different time instances, corresponding to revolutions 1, 2, 4, and 7 in Fig. 2. The legend in subfigure a1 applies to all subfigures.

periments, the spanwise resolution was limited by the chosen PIV planes, but we envision digital image correlation to be an appropriate tool for future experimental campaigns.

3.4. Flow field results

Since the elastic response of the propeller appears to be quasi-steady, the flow fields are analyzed for hysteresis. Due to the large dimensions of the data, we only present selected results here, namely the ensemble-averaged vertical velocity $\langle v \rangle$, for revolutions 1, 2, 4, and 7 for $r/R = 0.6$. Profiles at $x/c_x = 0.1, 0.3, 0.5, 0.7$, and 0.9 are depicted in Fig. 8, where the coordinate system is centered at the leading edge. We see that the profiles collapse for almost all chord positions (columns) and all presented time instances (rows). Even though the thrust coefficient shows significant hysteresis at all points for which velocity is plotted, the flow over the blade does not show this thrust difference at all. However, it cannot be excluded that this is due to the limited resolution

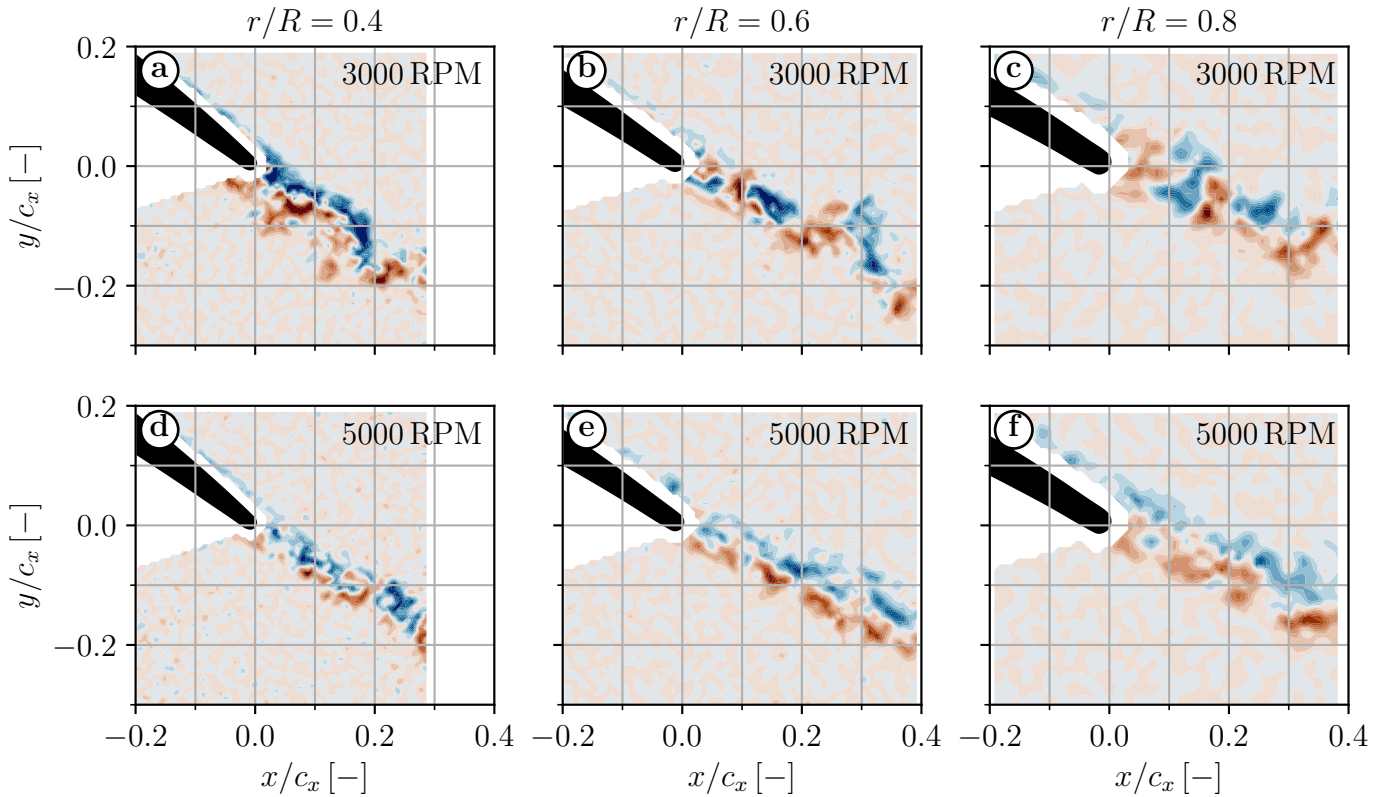


Figure 9. Instantaneous spanwise vorticity around the trailing edge between 3000 (a–c) and 5000 RPM (d–f). The spanwise locations are indicated by the title of each column.

of the PIV setup as the work of Toppings & Yarusevych (2024) shows separation occurring mostly close to the surface of the blade. Therefore, we continue with an analysis of the local wakes to get an idea about the state of the boundary layer.

To demonstrate the idea behind the wake analysis, Fig. 9 shows the spanwise vorticity ω_z for random snapshots in the trailing edge region in the area $(x/c_x, y/c_x) \in [-0.2, 0.4] \times [-0.3, 0.3]$, where the coordinate system is centered on the trailing edge. At the minimum speed of 3000 RPM (Figs. 9a,b,c), the vorticity shows large coherent vortices. These are most pronounced at $r/R = 0.6$ and 0.8 , since the normalized wake region at $r/R = 0.4$ is smaller, since the chord is larger. In comparison, the snapshots at 5000 RPM (Figs. 9d–f) show different vortices which are smaller and appear to be in two different layers, particularly for $r/R = 0.6$ and 0.8 . These observations are consistent with the literature (Yarusevych et al., 2006; Grande et al., 2021), where the vortices are large when the flow is separated (3000 RPM) and small when it is attached near the trailing edge (5000 RPM).

To better quantify the observations, we analyze the spatial structures of the vertical velocity of the leading POD mode in Fig. 10, computed from the velocity in the same region as the one of Fig. 9. The separated states (Fig. 10a–c) show coherent, large vortices in the entire wake region. For $r/R = 0.4$ at 5000 RPM, the first POD mode (Fig. 10d) likewise shows vortex shedding with a

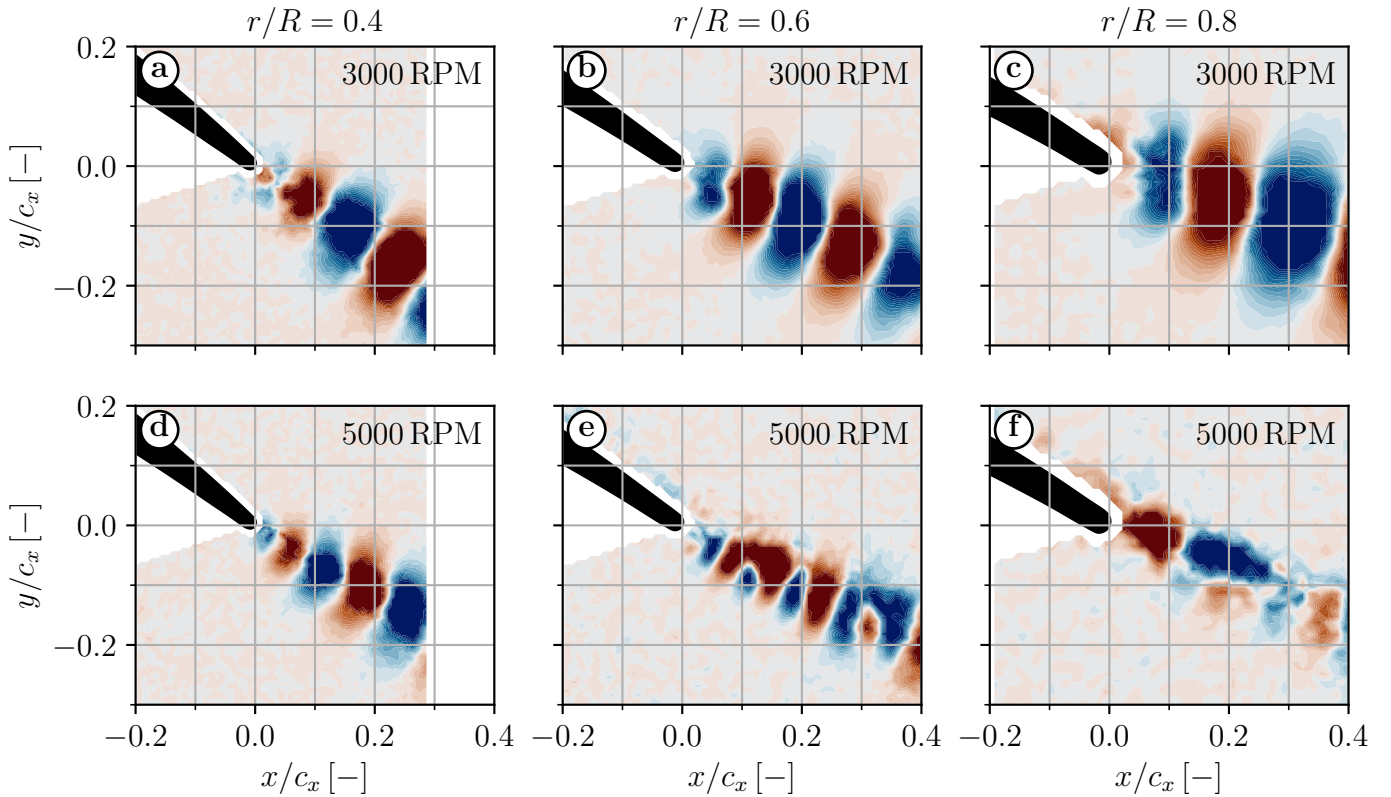


Figure 10. Spatial distribution of the leading POD mode of the vertical velocity around the trailing edge between 3000 (a-c) and 5000 RPM (d-f). The spanwise locations are indicated by the title of each column.

similar shape as for 3000 RPM. It seems that even though the instantaneous vorticity was different, the most dominant mode is still that of a non-reattached flow. In contrast, the 5000 RPM cases at $r/R = 0.6$ and 0.8 (Fig. 10e,f) show a smeared out, large vortex extending from $x/c = 0$ to 0.2 , which then switches to small, less coherent vortices, associated with a reattached LSB. Subsequent modes also show this behavior of small shed vortices in the wake. These findings indicate that over the course of the acceleration, the flow at $r/R = 0.6$ and 0.8 changes between separated and reattached state while the inboard section remains separated. There are a multitude of potential explanations for this, ranging from geometric factors, since pitch and chord are different, to three-dimensional effects, such as Coriolis forces and the influence of the tip vortex.

We now look at the unsteady evolution of the dominant POD structures and compare them to quasi-steady conditions. To this end, Fig. 11 shows the spatial structures of the first POD mode of the vertical velocity of the unsteady case at $r/R = 0.6$ at the same time instances of the velocity profiles in Fig. 8. The figure also contains the dominant quasi-steady POD mode at the closest available quasi-steady rotational speed. At the start of the acceleration (Fig. 11a), regular, large-scale vortex shedding is observed, which is also present in quasi-steady conditions at (Fig. 11e). This indicates quasi-steady behavior, as also lower rotational speeds show the same dominant POD mode. At 3523 RPM (Fig. 11b, the moment of largest thrust difference in Fig. 6b),

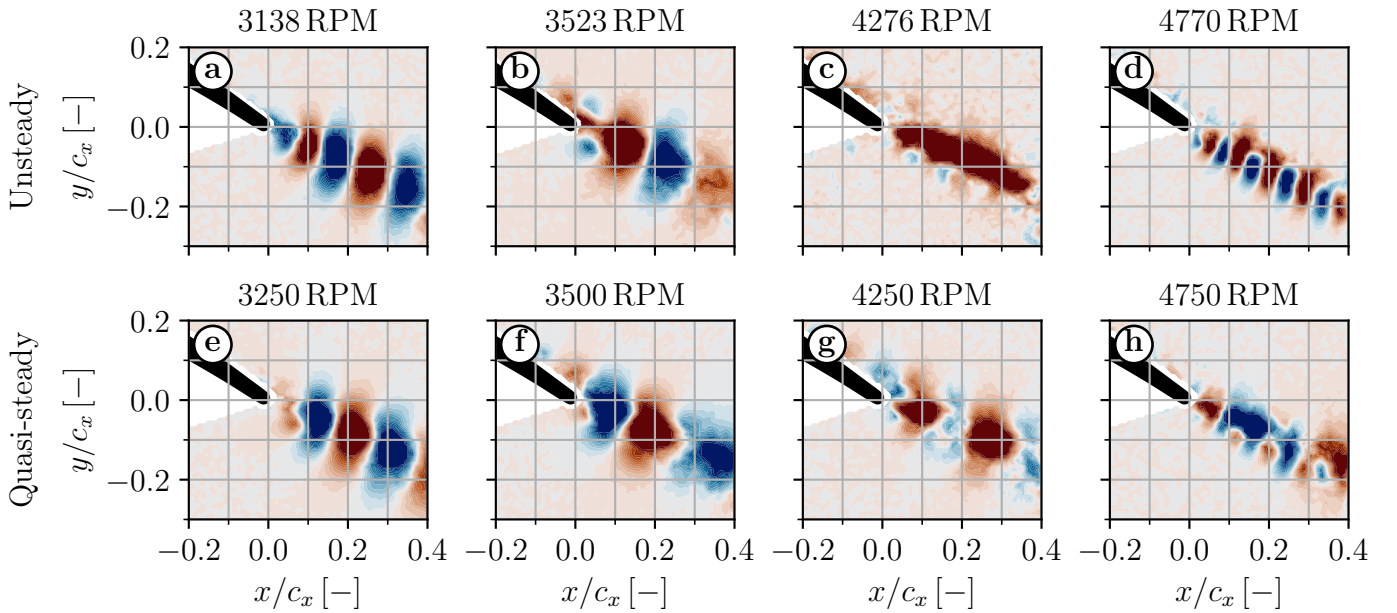


Figure 11. Spatial distribution of the leading POD mode of the vertical velocity $\langle v \rangle / U_{\text{blade}}$. The unsteady modes (a–d) correspond to the time instances in Fig. 8 at revolutions 1, 2, 4, and 7, and the steady modes (e–h) are extracted at the closest quasi-steady rotational speed.

the corresponding quasi-steady POD mode (Fig. 11f) exhibits very similar behavior. Large vortices cover the wake, and some smaller structures are present over the surface at the trailing edge. This would again indicate quasi-steady velocity fields, even though the thrust coefficient shows strong differences, and also the velocity profiles over the blade vary significantly. In contrast, the largest difference in the POD mode occurs at 4276 RPM (Fig. 11c), where a single, large structure is present in the upper part of the wake, while the lower one shows small vortices. The corresponding quasi-steady field (Fig. 11g) shows a different structure with more coherent vortices and structures present over the trailing edge of the airfoil. Afterward, at 4770 RPM (Fig. 11d), the wake shows the characteristics of an attached LSB with regular, small scale vortices. This appears to be quasi-steady, as also the quasi-steady field at (Fig. 11h) shows structures which are very similar in their position and spatial frequency. Further analysis is needed to characterize and understand this behavior at different spanwise locations, as the LSB properties of a local section are likely a global phenomenon that happens over the entire blade.

4. Summary and Conclusions

We investigated an accelerating propeller at low Reynolds numbers with thrust measurements and phase-locked particle image velocimetry of the local airfoil flow field at spanwise locations of $r/R = 0.4, 0.6$, and 0.8 . The propeller was characterized with open-loop step responses in the rotational speed between 3000 and 5000 RPM. Significant hysteresis with up to 10 % difference in

the thrust coefficient was observed during the initial transient, where acceleration is strongest.

Extensive pre-processing was required to remove reflections of both the propeller hub in the background and laser flare near the blade surface. The resulting pre-processing also allowed to characterize the vertical displacement of the propeller blade and the additional twist as a function of the rotational speed. The results indicate a quasi-steady response of the deflection and twisting of the blade. Slightly higher r.m.s. values of the deflection were observed, but these do not seem to affect the mean system response.

The flow field analysis at $r/R = 0.6$ reveals no hysteresis of the local flow over the airfoil, in none of the regions. The velocity field outside the boundary layer shows no differences and the resolution of the PIV setup is insufficient to obtain data points near the surface. Instead, we analyze the wake with proper orthogonal decomposition, which reveals that the sections at $r/R = 0.6$ and 0.8 vary between separated and reattached flow states, while the inboard section at $r/R = 0/4$ always remains separated. The analysis of the dominant POD mode suggests that the initial stages of the acceleration are quasi-steady, while a snapshot at higher RPMs indicates differences to quasi-steady conditions, which then cease towards the end of the acceleration. Further analysis of the entire spanwise variation of the velocity field will be carried out in the future to better understand the observed phenomena.

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