

Experimental investigation of transient inflow and wake response of a low-Reynolds two-bladed propeller

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ABSTRACT

The growing use of unmanned aerial vehicles (UAVs), together with their deployment in increasingly demanding operating environments, raises the need for a better understanding of transient propeller aerodynamics. Small UAV propellers typically operate at low chord-based Reynolds numbers, of order $\mathcal{O}(10^4 - 10^5)$, and are often modeled using quasi-steady assumptions. At these scales, the coexistence of laminar separation, transition sensitivity, high rotational speeds, and compact three-dimensional wake structures makes both numerical prediction and experimental flow-field characterization particularly challenging. This partly explains why transient inflow and wake dynamics remain poorly documented. In this study, phase-locked PIV measurements are performed in the propeller meridian-plane to investigate the transient inflow and wake response of a low-Reynolds-number two-bladed propeller under steady conditions and rotational-speed ramps. During experiments, load measurements reveal a hysteresis in the thrust coefficient between acceleration, deceleration, and steady operation. The inflow field was first examined by extracting the axial velocity along the blade leading-edge line, in order to identify a possible transient signature. However, the resulting profiles did not show a clear systematic difference between the different regimes. In contrast, the wake analysis indicates more noticeable modifications, particularly in the position and shape of downstream vortical structures. These results suggest that the transient load hysteresis is more likely associated with wake adaptation than with a directly measurable inflow variation in the investigated plane.

1. Introduction

In recent years, unmanned aerial vehicles (UAVs), and particularly small-scale UAVs, have become increasingly widespread, with applications spanning a broad and continuously expanding range of sectors (Zhang & Zhu, 2023). As their operational envelope expands toward more demanding applications, these vehicles are increasingly exposed to disturbed flow environments

and rapid manoeuvres that impose fast variations in propeller rotational speed. The resulting transient changes in blade loading and wake development may not be captured by quasi-steady aerodynamic assumptions.

Recent studies at low chord-based Reynolds numbers, typically of order $\mathcal{O}(10^4 - 10^5)$, have shown that aerodynamic loads may exhibit pronounced history dependence under transient operating conditions, and experience the formation of a laminar separation bubble (LSB). At the airfoil scale, experimental investigation using simultaneous force measurements and PIV, showed that stall and reattachment transients at low Reynolds number are associated with hysteresis in the lift response and with the formation and bursting of a LSB (Toppings & Yarusevych, 2025). For rotating propellers, numerical simulations by Grava et al. (2026) showed hysteresis in thrust and torque coefficients during rotational-speed ramps. Similarly, Ratz et al. (2026) reported experimental deviations in the thrust coefficient of approximately +6% during step-up operation and -5% during step-down operation for a small blade twist angle.

Transient aerodynamic effects have long been recognized in rotorcraft aerodynamics, where Reynolds numbers are typically much larger than those encountered by small UAV propellers. To account for these phenomena, dynamic-inflow models based on first-order lag formulations have been developed and incorporated into rotorcraft aerodynamic models for several decades (Chen, 1989). While the earliest formulations relied heavily on empirical tuning and rotor-specific calibration, more recent studies have provided direct experimental validation of the dynamic inflow response using phase-resolved PIV at different excitation frequencies (Mortimer & Sirohi, 2025). In contrast, low-Reynolds-number UAV propellers are still predominantly modeled using quasi-steady aerodynamic assumptions, despite growing evidence of hysteresis and transient load deviations under unsteady operating conditions. Direct flow-field measurements remain scarce in this regime, partly because the relevant transient time scales are short, the wake structures are compact and strongly three-dimensional, and the measured fields are highly dependent on blade phase.

To address these limitations, the present work performs phase-locked PIV measurements in the rotor mid-plane of a small UAV propeller under steady operation and rotational-speed ramps. By acquiring the velocity fields at a fixed blade azimuth, the deterministic blade-passing contribution is preserved rather than smeared in the ensemble average, enabling direct comparison between steady, accelerating, and decelerating cases at equivalent rotor phases. The objective is to assess whether transient RPM variations produce measurable differences in the inflow and near-wake fields at comparable rotational speeds, and whether these differences can help interpret the observed load hysteresis.

2. Methodology

2.1. Propeller and operating conditions

For the present low-Reynolds-number investigation, an off-the-shelf propeller from a Holybro X500 V2 drone was used. The selected two-bladed propeller is denoted X500 V2 1045, and has an original diameter of 254 mm and a nominal pitch of 114.3 mm. To reproduce higher effective inflow angles of attack that are representative of rapid drone manoeuvres, the propeller was modified using a central mounting piece (see purple piece in Fig. 2a). An additional collective pitch of $\beta = 5^\circ$ was imposed and resulted in a final propeller diameter of $D = 310.5$ mm.

On the hardware side, the propeller is driven by the brushless DC motor T-motor AT3520 550KV and controlled using the electronic speed controller (ESC) T-Motor AT75A 2–6S. The rotational speed is measured with a CUI AMT11 incremental encoder with a resolution of 2048 pulses per revolution. The propeller loads were measured using a FUTEK QMA150 load cell with a 100 N capacity. All components were mounted vertically on a dedicated propeller test stand (see Fig. 2a).

On the instrumentation side, the motor control was handled by a Raspberry Pi 5, which generated a hardware pulse-width modulation (PWM) signal sent to the ESC. The Raspberry Pi 5 was also equipped with an MCC 128 DAQ HAT, used to acquire the load-cell signal at a sampling frequency of 10 kHz with 16-bit resolution. The encoder signal was processed by an Arduino Giga R1 WiFi, which counted the number of encoder pulses over 2 ms intervals, providing an effective rotational-speed acquisition frequency of 500 Hz.

The experiments were conducted under two operating modes: steady and transient conditions. The steady cases consisted of discrete rotational speeds ranging from 2750 to 5250 RPM, with increments of 250 RPM. For the transient cases, open-loop rotational-speed step responses were performed in both acceleration and deceleration between 3000 and 5000 RPM. To determine the appropriate phase-locked sampling locations along the ramps, acceleration and deceleration tests were first repeated 500 times and ensemble-averaged to obtain representative mean RPM trajectories.

2.2. PIV experimental setup

The PIV setup was installed in the W-tunnel at TU Delft, although no external inflow was imposed in the present experiments (see Fig. 2b). The laser sheet was generated from the laser beam using a combination of spherical and cylindrical lenses, producing a sheet focused in the field of view (FOV) with an approximate thickness of 1.5 mm. The camera used was a LaVision Imager sCMOS with a resolution of 2560 px $\times$ 2160 px. The optical system was equipped with an AF Micro-Nikkor lens with a focal length of $f=35$ mm. The main PIV components and specifications are summarized

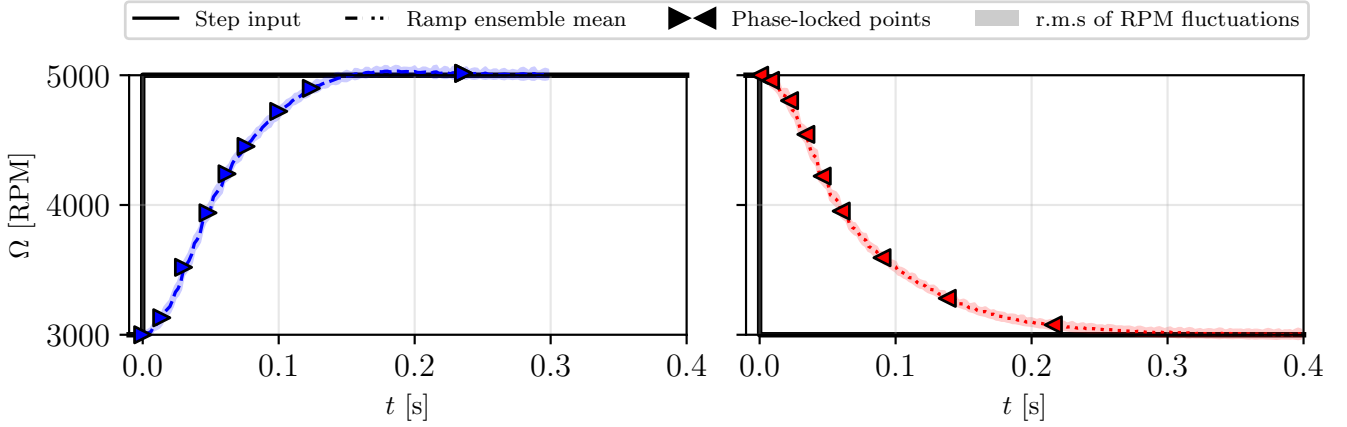


Figure 1. Rotational-speed open-loop step responses for the acceleration and deceleration cases. Dashed and dotted lines indicate the ensemble-averaged RPM responses over 500 repetitions, while triangular markers indicate the selected phase-locked sampling points along the acceleration and deceleration ramps.

in Tab. 1.

The FOV is located in a half-plane perpendicular to the rotor disk and contains the propeller axis. The field of view captures both the inflow region upstream of the disk and the initial vortical structures shed by the blade. The FOV extends approximately $1.72 R$ in the radial direction and $2.05 R$ in the axial direction. Two blade azimuthal positions were considered in this study. The main PIV measurements were acquired at $\psi = 0^\circ$, for which the blades are perpendicular to the measurement plane, avoiding blade obstruction. This phase constitutes the primary dataset analysed in the present work, as shown in Fig. 2c. Additional acquisitions were performed at $\psi = 90^\circ$, where the blade lies in the measurement plane, in order to identify the blade position for each operating condition, as shown in Fig. 2d.

A local reference frame is defined using the axial (z) and radial (r) directions (see Fig. 2d). The axial coordinate is oriented toward the incoming flow, while the radial coordinate is directed outward from the propeller axis. The corresponding velocity components are denoted by u and v , respectively, and the in-plane velocity magnitude is defined as $u = \sqrt{u^2 + v^2}$. In the following analysis, the 250 instantaneous velocity fields are ensemble-averaged and denoted by angle brackets, $\langle \cdot \rangle$. All velocity components were normalized by the blade-tip velocity, ωR , where ω is the rotational speed expressed in rad s^{-1} and R is the propeller radius expressed in m.

The data were processed using the PaIRS software (Paolillo & Astarita, 2024) with a multi-pass interrogation scheme using window sizes of 96×96 , 48×48 , and 24×24 pixels, with overlaps of 50%, 75%, and 75%, respectively.

Table 1. Main specifications of the PIV measurement system.

Camera	LaVision Imager sCMOS
Objective	AF Micro-Nikkor 35 mm
Field of view	$2.05 R \times 1.72 R$
Magnification	0.052
Imaging resolution	8.1 px/mm
Laser source	Quantel Evergreen EVG00200 Nd:YAG
Maximum pulse energy	200 mJ
Separation times	84 – 160 μ s
Seeding fluid	SAFEX-Inside-Nebelfluid, water-glycol mixture
Median particle size	1 μ m

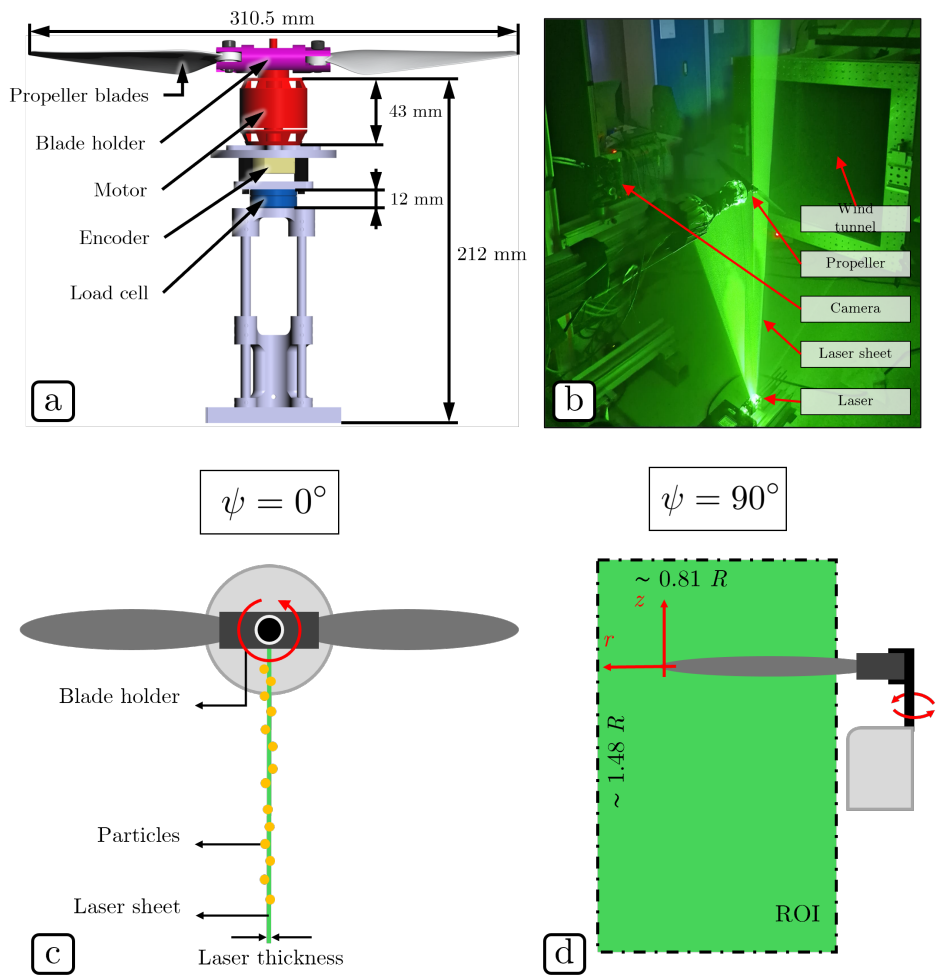


Figure 2. PIV experimental setup used for the measurements. (a) schematic side view of the rotor rig (b) photograph of the experimental setup. Simplified schematic representation of the region of interest for blade azimuthal locking at (c) $\psi = 0^\circ$ and (d) $\psi = 90^\circ$.

2.3. Phase-locked acquisition strategy

The PIV acquisition frequency was limited to 15 Hz, while the acceleration and deceleration ramps lasted only 0.3 s and 0.4 s, corresponding to characteristic frequencies of approximately 3.33 Hz and 2.5 Hz, respectively. In addition, during the transient ramps, the propeller rotational frequency varied from about 50 to 83.3 Hz. As a result, a continuous time-resolved PIV acquisition over the full ramps could not provide sufficient temporal resolution, especially during the initial stage of the acceleration, where the flow evolves most rapidly. Instead, the transient response was reconstructed from repeated phase-locked acquisitions at selected integer blade revolutions, allowing multiple operating points to be sampled along the ramps while preserving a fixed blade azimuth. This approach makes it possible to characterize the vortical structures while also providing ensemble-averaged quantities from which statistical information on the flow can be inferred.

Each acquisition episode consisted of an acceleration ramp followed by a deceleration ramp. A short dwell time was imposed between the two transitions. The target sampling locations were prescribed as integer-revolution lists, $N_{\text{rev}}^{\text{up}} = 0, 1, 2, 3, 4, 5, 7, 9, 12, 17$ for acceleration and $N_{\text{rev}}^{\text{do}} = 0, 1, 2, 3, 4, 5, 7, 10, 14$ for deceleration, in order to cover the full transient response from the onset of the ramp to the final steady condition. A stagger of six revolutions was then applied: for a given offset o , only points satisfying $N_{\text{rev}} \bmod 6 = o$ were acquired, and the offset was varied between repeated episodes to cover the complete set of points in both directions. Sampling points were then selected at integer numbers of blade revolutions along these mean trajectories in order to cover the full transient phase of both ramps, as shown in Fig. 1.

3. Results

3.1. Aerodynamics characterization

The aerodynamics of the propeller can be characterized, among other quantities, by the thrust force T or by its non-dimensional form, the thrust coefficient. The latter is defined as $C_T = T/(\rho n^2 D^4)$, where ρ is the air density, n is the rotational frequency in revolutions per second, and D is the propeller diameter.

During the rotational-speed ramps, thrust measurements were acquired using the load cell, from which the thrust coefficient was computed. The evolution of C_T under steady, acceleration, and deceleration conditions is compared with the relative deviation between the steady and unsteady thrust coefficients, defined as $\Delta C_T = (C_{T,\text{steady}} - C_{T,\text{unsteady}})/C_{T,\text{steady}}$ and expressed as a percentage. Both quantities are shown in Fig. 3.

For visualization of the unsteady load measurements, a third-order Butterworth low-pass filter with a cut-off frequency of 30 Hz was applied. The thrust coefficient exhibits a clear hysteresis be-

tween the steady and transient regimes. During acceleration, C_T increased by up to 7.6% relative to the steady case, whereas during deceleration the deviation reached -5.5% . This trend is opposite to that reported in previous investigations of history-dependent aerodynamic effects (Grava et al., 2026; Ratz et al., 2026), while the order of magnitude remains similar.

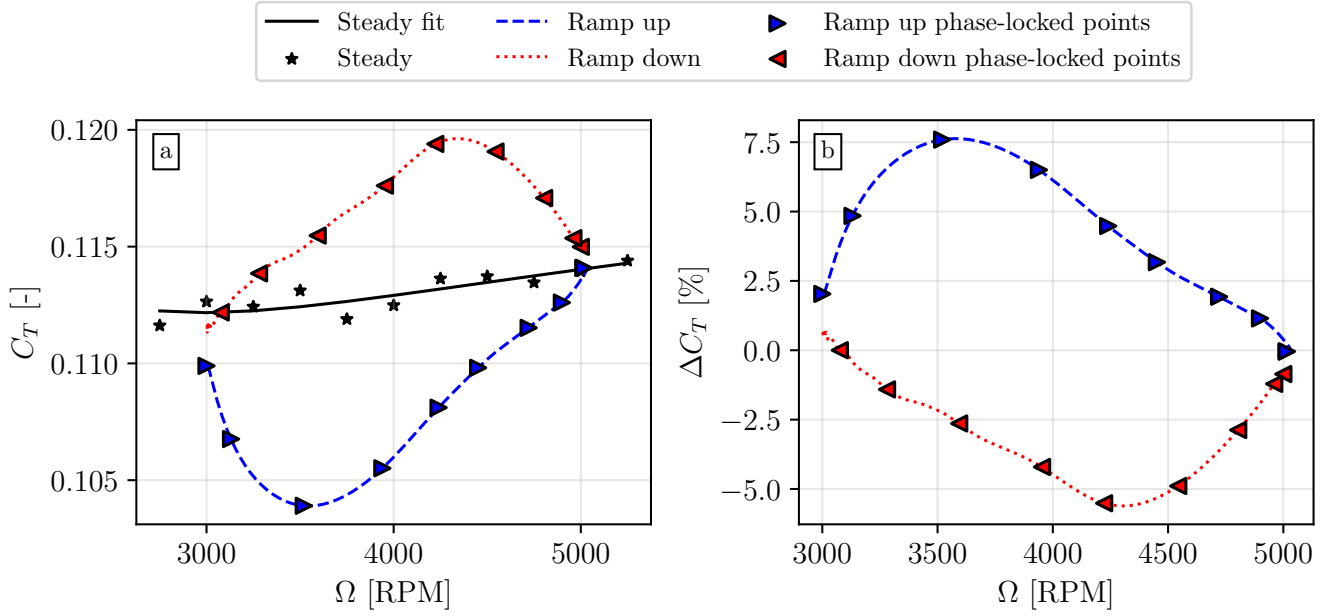


Figure 3. Thrust coefficient (a) and relative difference between steady and unsteady thrust coefficient (b) evolution with rotational speed.

3.2. Aeroelastic blade deformation

Changes in rotor loading induce blade deformation, which is quantified here using the blade deflection angle. This deviation is defined as the angle between the blade span and the horizontal plane. For this study, it was measured from 50 phase-locked image pairs acquired at $\psi = 90^\circ$, where the blade lies within the laser sheet. For each operating condition, the hub and tip positions were manually identified.

To improve the manual blade localization and reduce the influence of small blade-position jitter between phase-locked frames, a temporal median reconstruction was applied to the 50 acquired frames. The blade position was then manually identified from the image gradient in the axial direction. This procedure suppresses moving structures and retains stationary features, allowing the blade position to be more clearly identified. Fig. 4b shows the reconstructed image at $\Omega = 4000$ RPM, together with the identified tip and hub reference points. Because the original propeller was modified with a central mounting piece, shown in purple in Fig. 2a, the visible blade reference line within the ROI does not extend to the actual hub center. Therefore, the hub reference point was

defined as the point within the ROI located closest to the hub. The line connecting this reference point to the blade tip is used as an approximate representation of the blade leading-edge direction. The angle between this line and the horizontal direction is then defined as the deflection angle α .

The evolution of the deflection angle with rotational speed is shown for the steady and unsteady cases in Fig. 4a. For all cases, the deflection angle increases approximately linearly with RPM, consistent with trends reported for similar drone propellers (Nowicki, 2017). However, both ramp cases exhibit systematically lower deflections than the steady operating conditions. Therefore, no clear relationship could be established between the measured blade deflection and the hysteresis observed in the aerodynamic loads. Moreover, the present analysis does not account for local blade-twist deformation under varying loading, which could also affect the effective inflow angle of attack and, consequently, the aerodynamic loading.

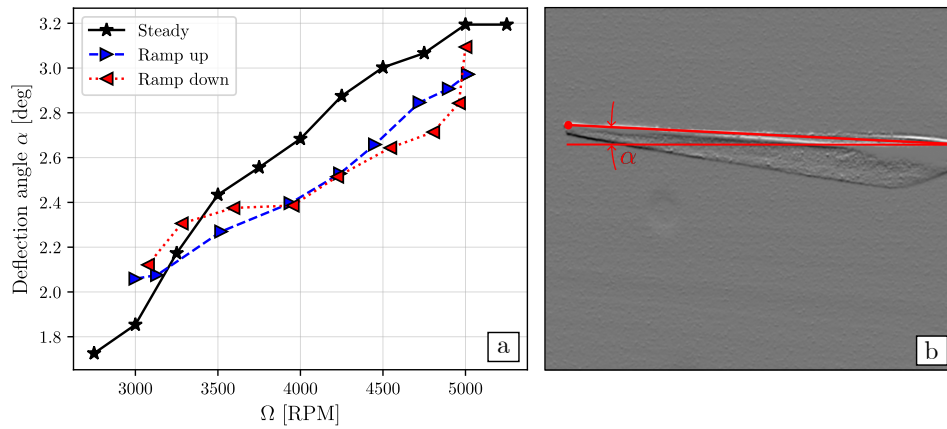


Figure 4. Blade-deflection characterization. (a) Blade deflection angle α as a function of rotational speed Ω for steady and transient ramp conditions. (b) Reconstructed blade image obtained from the median axial pixel gradient over $N_f = 50$ frames for the steady case at 4000 RPM.

3.3. Steady phase-locked velocity fields

Figure 5 shows the processed velocity fields for the steady case at $\Omega = 4000$ RPM. The velocity-magnitude field in Fig. 5a illustrates the contraction of the flow toward the propeller disk, with fluid entrained from both the upstream and lateral regions of the field of view. Downstream of the blade, several coherent vortical structures can be identified and are convected into the wake. The blade position is represented by a red line on each map. This position corresponds to the blade location one quarter of a rotation before. The deflection measured in the previous section was applied to each steady and unsteady case to account for the corresponding blade deformation.

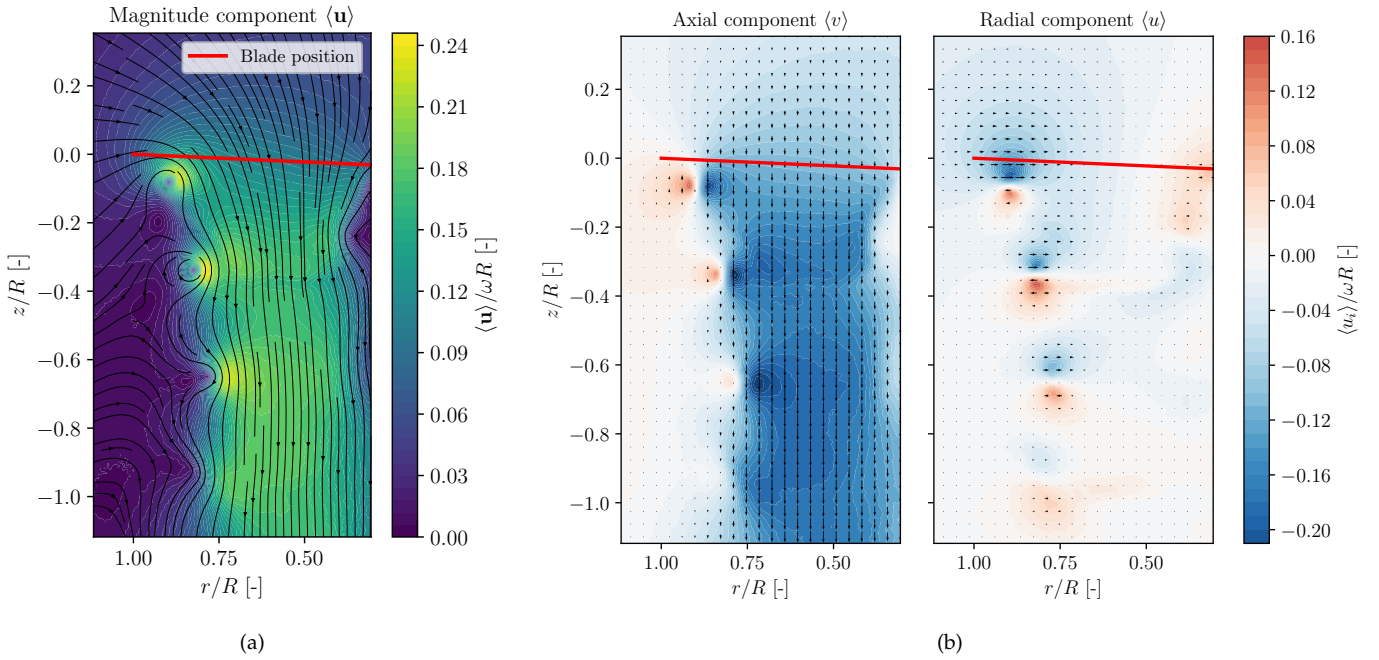


Figure 5. Ensemble-averaged PIV fields for the steady case at 4000 RPM and $\psi = 0^\circ$: (a) non-dimensional in-plane velocity magnitude and (b) non-dimensional axial and radial velocity components. The red lines indicate the blade trailing-edge position corresponding to $\psi = 90^\circ$.

3.4. Comparison of steady and transient flow conditions

To compare the flow dynamics between steady and unsteady conditions, two complementary regions are investigated: the inflow, using the known blade position as a reference, and the wake downstream of the blade.

3.4.1. Inflow at the blade leading edge

To investigate dynamic effects in the measured flow fields, an extraction procedure inspired by Blade Element Momentum Theory (BEMT, Bramwell et al. (2001)) was applied. In this framework, the induced velocity is defined at the rotor disk in an axial reference frame. Since the PIV fields are phase-locked, the velocity profile can only be extracted along the radial line corresponding to the measured azimuthal position. The blade leading-edge line, shown by the solid red line in Fig. 5, was therefore used as the extraction line.

Figure 6 shows the ensemble-averaged profile along the blade trailing-edge span, together with the instantaneous profiles obtained from the 250 PIV image pairs. The largest deviations between instantaneous profiles are observed near the hub, approximately between $r/R = 0.3$ and 0.4 , and near the blade tip, approximately between $r/R = 0.85$ and 1 . This increased scatter is associated with the intersection of the extraction line with the hub and tip vortical structures, where strong

local velocity gradients make the sampled velocity more sensitive to cycle-to-cycle variations in vortex position, vortex strength and blade phase. The ensemble-averaged profile therefore provides the repeatable mean inflow behaviour along the blade span.

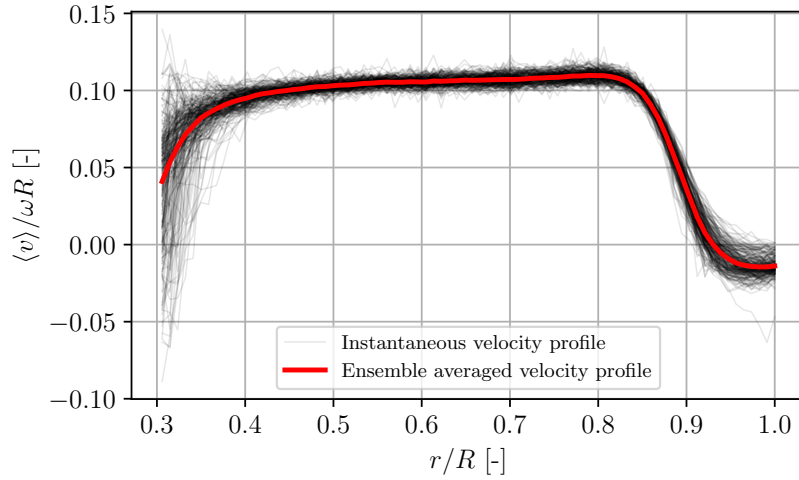


Figure 6. Non-dimensional axial velocity profile extracted along the blade position at $\psi = 90^\circ$ for the steady case at 4000 rpm. The red line denotes the ensemble-averaged profile over N_{frames} instantaneous snapshots, shown in light grey.

Next, Fig. 7 compares the same normalized velocity of all acquired rotational speeds in steady conditions and for the transient acceleration and deceleration ramps. Overall, the profiles exhibit similar trends in both steady and unsteady conditions. Although the profiles tend to increase globally with rotational speed, no clear systematic shift can be identified between the steady and transient cases. Therefore, based on this line extraction alone, no definitive conclusion can be drawn regarding a measurable inflow lag. The largest variations are observed near the blade tip, where the extraction line intersects the tip-vortex region. In this area, changes in blade loading with rotational speed may slightly modify the position and strength of the first tip vortex, leading to more pronounced variations in the extracted profiles.

These results provide a first indication of the limitations of the present inflow-line analysis. The lack of trend in the results might not imply that the transient inflow response is absent, but rather that no sufficiently large inflow variation is resolved by the present extraction method to directly explain the hysteresis observed in the aerodynamic coefficients in Fig. 3. It should also be noted that the velocity fields are acquired at $\psi = 0^\circ$, whereas the extraction line corresponds to the blade position at $\psi = 90^\circ$. The analysis therefore samples the flow associated with a blade passage after approximately one quarter of a revolution. If the transient inflow signature is localized very close to the blade or evolves rapidly during this azimuthal interval, part of the effect may already have been convected, redistributed, or attenuated before reaching the investigated line. Consequently, this motivates the subsequent examination of the wake structure, where the history-dependent response may be more clearly expressed.

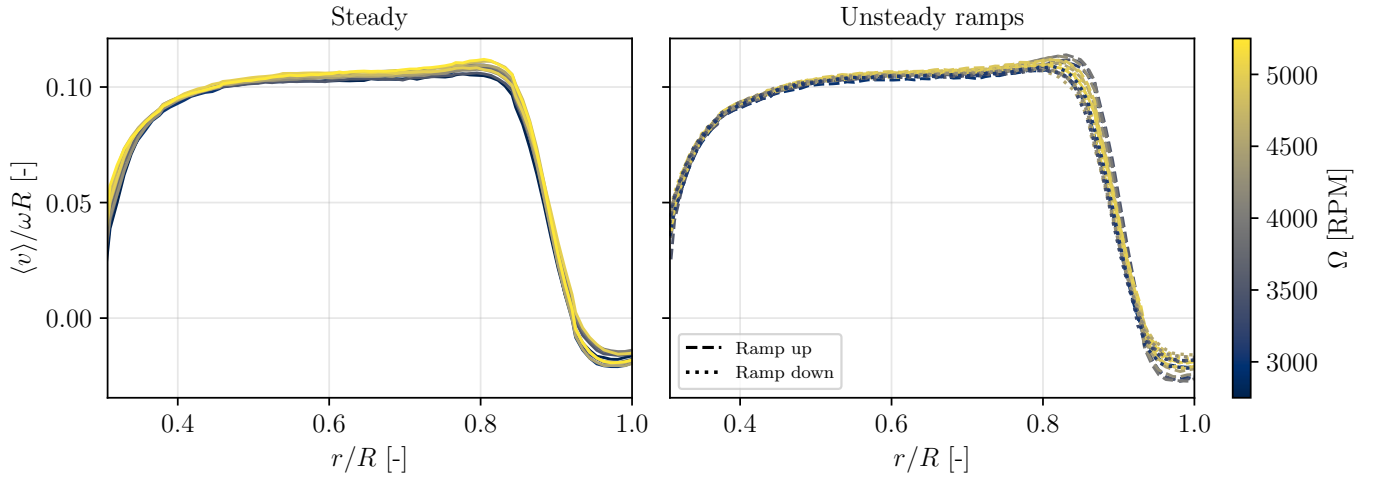


Figure 7. Ensemble averaged non-dimensional axial velocity profiles along the blade for all rotational speeds. Left plot corresponds to the steady case, while the right plot shows the unsteady ramp-up and ramp-down cases.

3.4.2. Wake flow

To further investigate the wake response, two locations are investigated. First, the non-dimensional in-plane velocity magnitude was extracted along several horizontal lines located within the wake. Figure 8 compares the velocity fields obtained under steady and transient conditions at comparable rotational speeds, together with the corresponding normalized velocity-magnitude profiles extracted along three wake lines. These extraction lines were positioned between the main vortical structures in order to focus the analysis on the mean wake velocity rather than on the local velocity extrema associated with individual vortex cores.

Since the transient phase-locked acquisitions were obtained at RPM values that do not exactly match the discrete steady operating points, each steady case was associated with the nearest available acceleration and deceleration samples in terms of rotational speed. For the case shown in Fig. 8, the acceleration case corresponds to $\Omega_{\text{up}} = 3520 \pm 36$ RPM, while the deceleration case corresponds to $\Omega_{\text{down}} = 3594 \pm 23$ RPM. Here, the values after the $\pm$ symbol denote the standard deviation of the instantaneous rotational speed over the phase-locked samples used to compute the ensemble-averaged velocity fields. This deviation is a consequence of the open-loop nature of the ramps, combined with residual electronic jitter and communication delays between the acquisition system and the absolute encoder used for azimuthal triggering. These values are compared with the closest steady condition, $\Omega_{\text{steady}} = 3500$ RPM. Nevertheless, the standard deviations associated with the transient RPM values indicate that the three cases remain sufficiently close in rotational speed to allow a qualitative comparison of the corresponding wake fields.

The wake core contracts radially as it is convected downstream in the axial direction. In the present measurement plane, the wake-core region extends approximately from $r/R = 0.45$ to 0.75

at $z/R = -0.2$, just downstream of the first hub and tip vortical structures, and from $r/R = 0.5$ to 0.7 at the lowest extraction line, located at $z/R = -0.8$. Outside this core region, the extracted velocity profiles are more strongly affected by the exact position of the surrounding vortical structures, which exhibit slight phase-to-phase and case-to-case variations. In the downstream region of the wake core, further from the blade passage, more noticeable differences are observed between the steady and transient cases, suggesting that the wake velocity field may retain a measurable signature of the acceleration or deceleration history. The same order of magnitude of deviation was observed on the other steady RPM with their closest unsteady points.

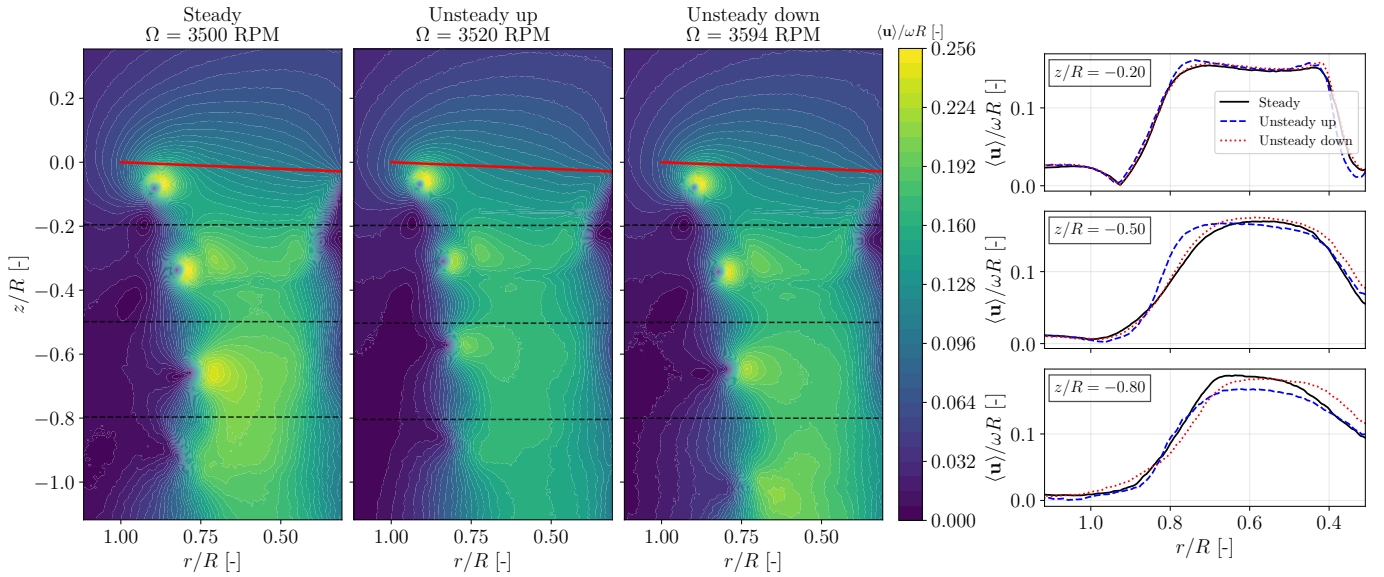


Figure 8. Non-dimensional in-plane velocity-magnitude fields under steady and transient conditions, together with velocity profiles extracted along horizontal wake lines at $z/R = -0.2$, -0.5 , and -0.8 . The cases correspond to $\Omega_{\text{steady}} = 3500$ RPM, $\Omega_{\text{up}} = 3520 \pm 36$ RPM, and $\Omega_{\text{down}} = 3594 \pm 23$ RPM.

After examining the wake-core velocity, the analysis was extended to the coherent vortical structures themselves. For this purpose, the out-of-plane vorticity was computed from the high-pass-filtered velocity fields in order to isolate the localized gradients associated with the tip vortices. The high-pass filtering was applied to the velocity fields by decomposing each velocity component into a low-pass background and a high-pass residual,

$$\langle u(r, z) \rangle = \langle u_{\text{LP}}(r, z) \rangle + \langle u_{\text{HP}}(r, z) \rangle, \quad \langle v(r, z) \rangle = \langle v_{\text{LP}}(r, z) \rangle + \langle v_{\text{HP}}(r, z) \rangle. \quad (1)$$

The low-pass fields were obtained using a Gaussian spatial filter with $\sigma = 5$ grid points, and the high-pass fields were defined as the residuals between the original normalized ensemble-averaged fields and the corresponding low-pass-filtered fields.

Figure 9 shows the resulting out-of-plane vorticity fields for the steady case and for the acceleration and deceleration transients, using the same near-RPM comparison as in Fig. 8. The black contours

correspond to a threshold based on the 97.5th percentile of the positive vorticity values. These contours highlight regions of strong positive vorticity under the selected sign convention. While the tip-vortex cores are among the dominant structures captured by this criterion, other vortical or shear-dominated regions, such as parts of the blade wake, may also be included. The contours are therefore used as a qualitative aid to compare the location and evolution of the main coherent vortical structures between the steady and transient cases.

The contours of all detected positive vortices are plotted in Fig. 10 for both steady and transient cases. The positions of the first two vortices remain broadly similar across the different operating conditions, suggesting a limited sensitivity of the near-wake vortex trajectory to both rotational speed and transient history.

However, differences become apparent from the third vortex onward, where both the position and shape of the contours start to vary between cases. Further downstream, the vortex contours become dispersed, indicating that the wake topology is more sensitive to changes in rotational speed and to the transient acceleration or deceleration history. Indeed, the third and fourth vortices were shed approximately $\psi = -450^\circ$ and $\psi = -630^\circ$ before the triggering position, respectively. These vortices are therefore older and have been convected farther downstream, making their position more sensitive to differences in rotational speed and transient history between the acceleration and deceleration cases. This can explain the slight displacement observed in their contours. For the fourth vortex, the steady cases at the lower RPM values also exhibit more coherent and well-defined contours, suggesting a stronger or less diffused vortical structure compared with the corresponding transient cases.

It should be noted that the present vortex-position analysis is based on the ensemble-averaged velocity fields. Therefore, the extracted contours represent the coherent structures that remain after averaging, rather than the position of each vortex in the instantaneous fields. This distinction is important, since cycle-to-cycle variations or phase jitter in the instantaneous vortex positions may lead to a more diffuse structure in the ensemble average. A more detailed analysis of the instantaneous vortex locations and their statistical dispersion would therefore be a useful extension of the present work.

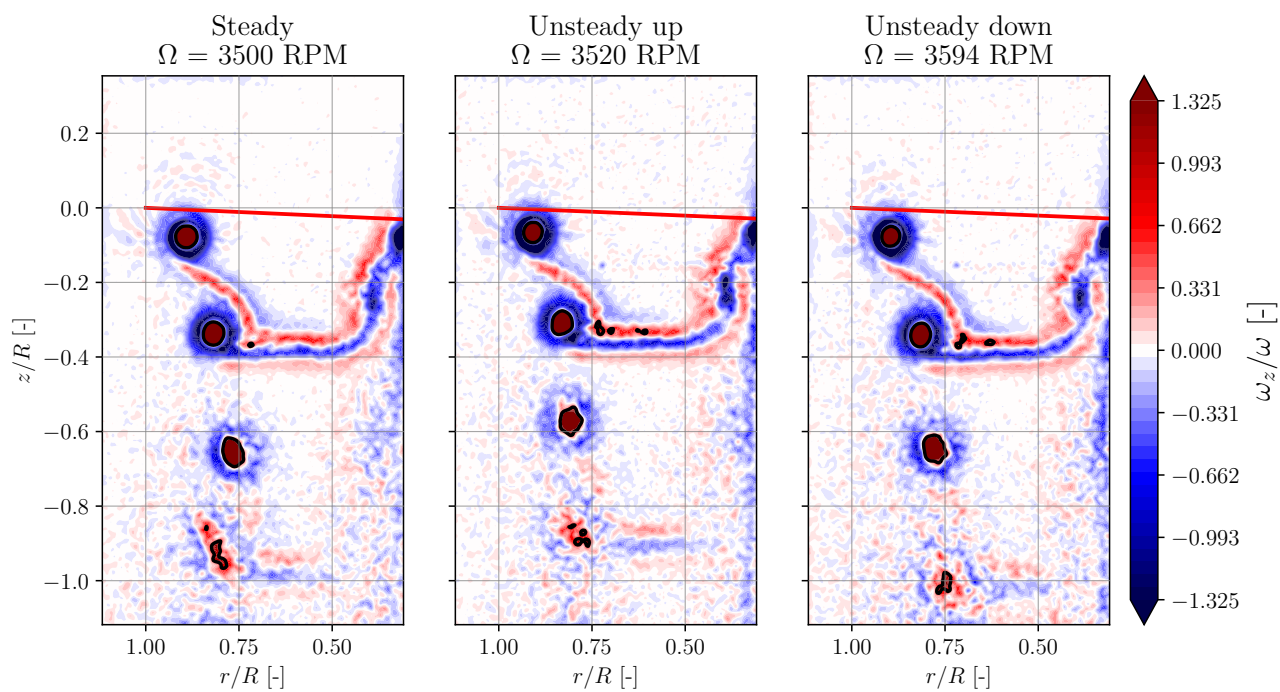


Figure 9. Out-of-plane vorticity fields for steady and transient conditions. Continuous black contours denote the threshold corresponding to the 97.5th percentile of positive vorticity.

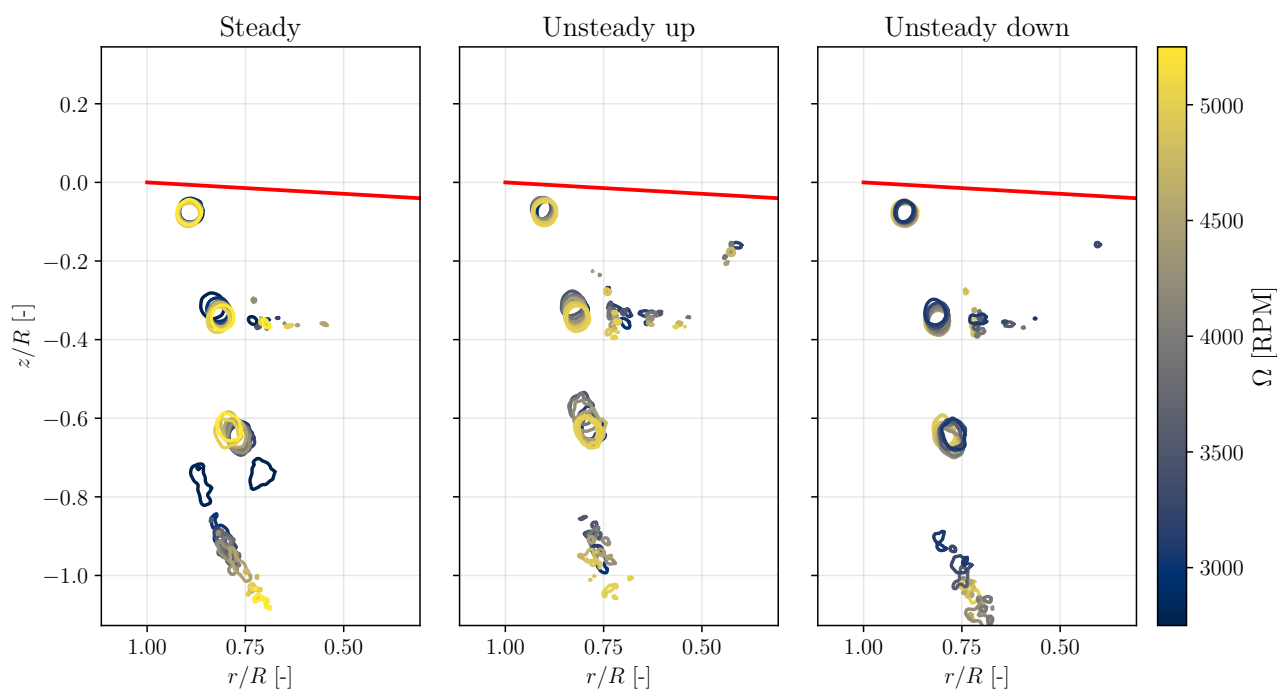


Figure 10. Positive vorticity contours for steady and transient conditions.

4. Conclusions

This study investigated the meridian-plane velocity field of a low-Reynolds-number two-bladed propeller using phase-locked PIV under steady and transient operating conditions. Open-loop acceleration and deceleration ramps were performed between 3000 and 5000 RPM. Load measurements showed a clear thrust hysteresis, with deviations reaching +7.6% during acceleration and -5.5% during deceleration relative to the corresponding steady conditions.

Several mechanisms were examined to interpret this behaviour. The blade-position measurements showed an approximately linear increase of coning angle with rotational speed, but no systematic difference between steady and transient cases. Similarly, the axial inflow profiles extracted along the blade position did not reveal a clear transient signature able to explain the load hysteresis.

The wake analysis provided the most promising indication. While the wake-core velocity showed only moderate differences, the vorticity contours revealed changes in the position and shape of the downstream vortices between steady and transient cases. These results suggest that the thrust hysteresis is more likely associated with wake adaptation than with a measurable inflow variation in the investigated plane.

Further investigations should extend the present phase-locked approach toward phase-resolved measurements over a wider azimuthal range, for example over at least 90° of blade rotation. This would allow the temporal evolution of the inflow and near-wake structures to be resolved more clearly, helping to identify the mechanisms responsible for the observed hysteresis. Such data could ultimately support the development of a reduced-order inflow-lag model suitable for control-oriented applications.

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