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Rahul Viswam

rahulviswam@yahoo.co.in

Indian Institute of Technology Bombay

Dhwanil Shukla

Indian Institute of Technology Bombay

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Wake Interactions and Aerodynamic Performance of Phase-Locked Tandem Rotors at Low Reynolds Numbers

Rahul Viswam and Dhwanil Shukla

Department of Aerospace Engineering, Indian Institute of Technology
Bombay, Mumbai, 400076, Maharashtra, India.

*Corresponding author(s). E-mail(s): rahulviswam@yahoo.co.in;

Abstract

Rotor–wake interactions strongly influence the aerodynamic performance of compact multirotor unmanned aerial vehicles operating at low Reynolds numbers. Overlapping rotor configurations such as tandem arrangements enable compact designs but introduce strong aerodynamic coupling between rotors. Although prior studies have shown that these interactions affect rotor performance, the influence of specific wake structures remains unclear, as most investigations rely on asynchronous rotor operation, where the relative azimuthal phase between rotors continuously varies.

The present study investigates the controlled interaction between upstream rotor wake structures and downstream rotor blades in tandem rotors and their effect on rotor performance. This is achieved by operating the rotors at precisely the same speed under phase-locked conditions (maintaining a fixed relative phase angle between rotor blades). Experiments are conducted over a range of rotor separations and relative phase angles. Ensemble-averaged flow fields for the phase-locked rotors are obtained using two-dimensional two-component particle image velocimetry (2D–2C PIV), together with simultaneous thrust and torque measurements.

The results show that the relative phase angle acts as an additional governing parameter, alongside rotor spacing, in determining rotor–wake interaction behavior and the resultant rotor performance. Certain phase configurations produce strong blade–vortex interactions and notable thrust variations, while others reduce wake interference. These findings provide new insight into rotor–rotor interaction mechanisms and demonstrate the potential of rotor phase control for improving the performance of compact multirotor systems.

Keywords: Synchronized rotors, Rotor phase angle, Phase-resolved PIV, Blade-vortex interactions, Low Reynolds rotors.

1 Introduction

Small multirotor unmanned aerial vehicles (UAVs) have rapidly expanded in both civilian and military applications, including aerial surveillance, inspection, environmental monitoring, and logistics. Their ability to hover and perform vertical takeoff and landing makes them particularly suitable for operations in confined environments where fixed-wing platforms are impractical.

Improving the aerodynamic efficiency of these systems while maintaining compact vehicle footprints remains an important design objective. Compact configurations enhance portability and maneuverability but typically require rotors to be placed in close proximity. As a result, rotor–wake interactions become an important factor influencing aerodynamic performance. Since most small UAVs rely on battery-based power systems, such interactions can significantly affect payload capability and endurance.

Overlapping rotor configurations, such as tandem or coaxial arrangements, offer one possible approach to achieving compact multirotor layouts. However, these configurations introduce strong aerodynamic interactions because the wake generated by one rotor directly influences the inflow of neighboring rotors [1]. Understanding these rotor–wake interactions is therefore essential for improving the performance of compact multirotor systems.

The wake structure of rotors operating at the low Reynolds numbers typical of small UAVs is strongly influenced by viscous effects. Compared with larger-scale rotors, low-Reynolds-number wakes exhibit comparatively larger vortex cores and stronger viscous diffusion, which can alter vortex trajectories and persistence [2]. Operation at low Reynolds numbers also degrades rotor performance, reducing thrust while increasing power requirements, whereas increasing the Reynolds number improves performance, with thrust increasing more rapidly than power consumption [3].

Rotor separation plays a critical role in determining aerodynamic performance in multirotor systems, even when rotor disks do not geometrically overlap. Significant thrust fluctuations have been reported at relatively small rotor separations in non-overlapping configurations, indicating that wake interactions remain influential even without direct rotor overlap [4]. For staggered tandem rotor arrangements, rotor spacing strongly affects both system performance and the evolution of wake interactions, with rotor–rotor interactions generally leading to adverse aerodynamic effects [5–10]. At the low Reynolds numbers typical of small UAVs, viscous effects further modify wake trajectories, causing deviations from classical momentum-theory predictions. Consequently, thrust losses arising from rotor–wake interactions cannot always be accurately predicted using simple momentum-based models [11–13].

For configurations involving overlapping rotors, aerodynamic performance is generally lower than that of isolated rotors due to strong rotor–wake interactions. In coaxial and tandem rotor arrangements, rotor spacing and the degree of overlap significantly influence system performance. The downstream rotor typically experiences stronger

adverse effects from the upstream rotor wake, while the influence on the upstream rotor is comparatively weaker [14, 15]. At the low Reynolds numbers relevant to small UAV operation, the details of the wake interaction between tandem rotors further influence performance and depend strongly on rotor separation and overlap [16].

Although prior studies have demonstrated the importance of rotor–wake interactions in multirotor systems, the precise influence of specific wake structures on rotor performance remains unclear. Most experimental and numerical studies evaluate rotor performance under asynchronous rotor operation, where the rotors operate at similar speeds but without maintaining a fixed relative azimuthal phase. Under such conditions, the downstream rotor encounters a continuously varying wake field, and the measured performance reflects a time-averaged combination of multiple interaction mechanisms. As a result, the individual effects of distinct wake features such as tip vortices and wake shear layers cannot be clearly isolated.

To address this limitation, the present study investigates rotor–wake interactions in tandem rotors operating under phase-locked conditions. In this configuration, both rotors rotate at identical speeds while maintaining a fixed relative azimuthal phase difference. This enables controlled interaction between specific wake structures generated by the upstream rotor and the blades of the downstream rotor. The experiments are conducted using a tandem rotor setup that allows systematic variation of the relative phase angle as well as the horizontal and vertical separation between the rotors.

The objective of this work is to map specific wake interactions to their corresponding effects on tandem rotor aerodynamic performance. The results demonstrate that the relative phase angle acts as an additional governing parameter, alongside rotor spacing, in determining rotor–wake interaction behavior. The study combines phase-resolved flow-field measurements obtained using 2D–2C particle image velocimetry (PIV) with simultaneous thrust and torque measurements to directly relate wake interaction mechanisms to rotor aerodynamic performance.

The remainder of the paper is organized as follows. Section 2 describes the experimental setup, measurement techniques, and operating conditions of the tandem rotor system. Section 3 presents and discusses the phase-resolved wake measurements obtained using particle image velocimetry, followed by the corresponding thrust and torque measurements. The key findings and implications of the study are summarized in Section 4.

2 Experimental Setup

2.1 Test Setup

An experimental setup was designed and fabricated to emulate synchronized tandem rotors operating under hover conditions. Figure 1 presents a schematic representation and a photograph of the setup. The system consists of two rotor assemblies, each comprising a rotor driven by a BLDC motor. Both assemblies are mounted on an in-house-built uniaxial torque cell that measures torque about the z -axis. This torque cell is subsequently mounted on a commercially available beam-type load cell, which measures thrust along the z -axis. The two rotors rotate in opposite directions and are oriented such that the induced wake is directed upward along the z -axis, resulting

in thrust production in the negative z -direction. The upstream rotor is defined as the rotor encountering the freestream flow first, while the downstream rotor operates within the wake generated by the upstream rotor. Horizontal separation (HS) and vertical separation (VS) define the relative rotor placement. The downstream rotor assembly is mounted on a vertically slideable support, enabling controlled variation of the vertical separation between the rotor disk planes. This vertical adjustment mechanism is itself mounted on a horizontally slid-able support, allowing independent variation of the horizontal separation between the thrust axes of the two rotors.

The upstream rotor assembly is mounted on a turntable that can pivot about the motor's rotational axis, thereby enabling controlled adjustment of the relative phase angle between the rotors. Each rotor assembly is equipped with an infrared (IR) count-slot sensor for rotational speed measurement and phase-angle determination. To facilitate this, each motor shaft carries two diametrically opposite counters, producing two pulses per revolution as they pass through the IR sensor. This configuration enables accurate phase-angle measurement between the two rotors by comparing the timing difference of the pulses generated as the counters pass their respective sensors.

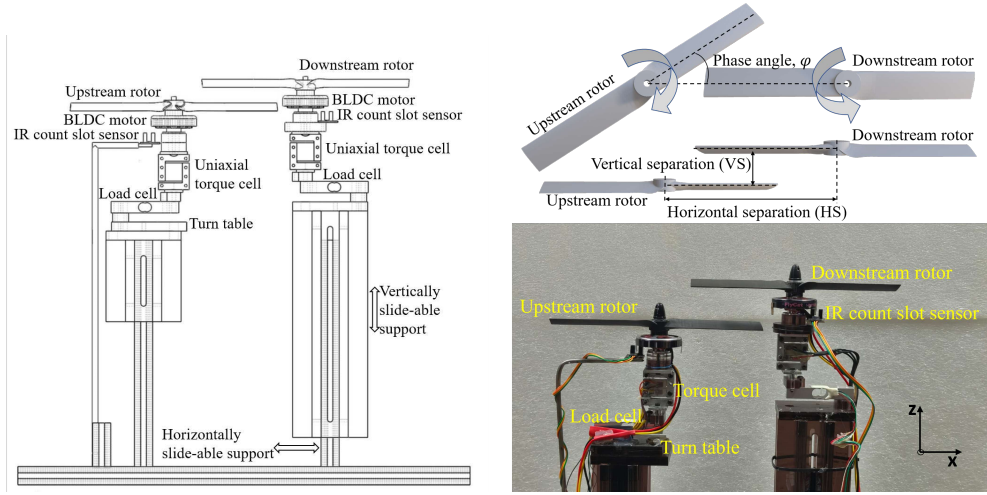


Fig. 1: Experimental setup, (left): schematic of the setup; (right, top): nomenclature of rotors ; (right, bottom): actual fabricated setup.

The BLDC motors are driven by an electronic speed controller (ESC), which are powered by a switched-mode power supply (SMPS). Motor speed is controlled through a feedback loop controller implemented on an Arduino Mega microcontroller. The output signals from the IR count-slot sensors are routed to a separate microcontroller, which processes these signals to compute the rotational speed (RPM) and the relative phase angle between the rotors. The computed RPM and phase information are displayed and logged on a connected computer for further analysis.

Throughout the present study, the downstream rotor is maintained as the leading rotor, while the upstream rotor operates with an imposed azimuthal lag relative to it. The experimental test matrix comprises a total of six horizontal separations (HS) between the rotor thrust axes. These separations are set to $1.3R$, $1.5R$, $1.75R$, $2.0R$, $2.25R$ (in increments of $0.25R$), and $2.8R$, where R denotes the rotor radius. Here $1.3R$ represents the maximum and $2.8R$ represents the minimum overlap of the rotors. At each horizontal separation, two vertical separations between the rotor disk planes are investigated, namely $0.2R$ and $0.4R$. For each combination of horizontal and vertical separation, six relative phase angles are imposed between the rotors, ranging from 0° to 150° in increments of 30° . The test matrix is shown in table 1.

Table 1: Test matrix covering rotor spacing (HS, VS), phase angle (ϕ)

Parameter	Values
Vertical Separation (VS)	$0.2R, 0.4R$
Horizontal Separation (HS)	$1.3R, 1.5R, 1.75R, 2.0R, 2.25R, 2.8R$
Phase Angle (ϕ)	$0^\circ, 30^\circ, 60^\circ, 90^\circ, 120^\circ, 150^\circ$

The rotors were operated at a nominal rotational speed of 5010 RPM. Thrust and torque measurements were acquired simultaneously during each test condition. Signals from the torque cell and the load cell were first routed through a signal-conditioning unit and subsequently fed into a National Instruments (NI) data acquisition (DAQ) system, where they were digitized and stored for further analysis. Data were sampled at a rate of 6012 Hz over a recording duration of 10 s for each test case. The rotors employed in the present study feature a custom-designed blade geometry with the properties as given in the table 2.

Table 2: Rotor specifications

Parameter	Values
Airfoil	NACA 23012
Diameter	9 inch (228.6 mm)
Chord	25 mm (constant)
Pitch	18° (constant)
RPM	5010

The rotor rotational speed is measured with an accuracy of ± 30 RPM, while the phase-angle measurement resolution is $\pm 1.4^\circ$. The uncertainties in thrust and torque measurements were estimated using the standard error of the mean (SEM), yielding an uncertainty of $\pm 0.045N$ for thrust and $\pm 1.47Nmm$ for torque.

2.2 PIV Setup

Flow-field measurements were performed using a two-dimensional, two-component (2D-2C) particle image velocimetry (PIV) system, available at Low Speed Experimental Aerodynamics Lab at Indian Institute of Technology Bombay. The system employed a double-pulsed Nd:YAG laser (Microvec), with each laser channel delivering an energy of 200 mJ per pulse. Image acquisition was carried out using a pco.panda DS 26 scientific CMOS camera, having a spatial resolution of 5120x5120 pixels. Synchronization between the laser pulses and the camera exposure was achieved using a high-speed timing unit (BNC-525) from Berkeley Nucleonics Corporation. Flow was seeded using an in-house-built seed generator with olive oil as the seeding medium. The seeder produced tracer particles with a mean diameter of $\sim 1\mu\text{m}$, which is well suited for external aerodynamic flow measurements [17].

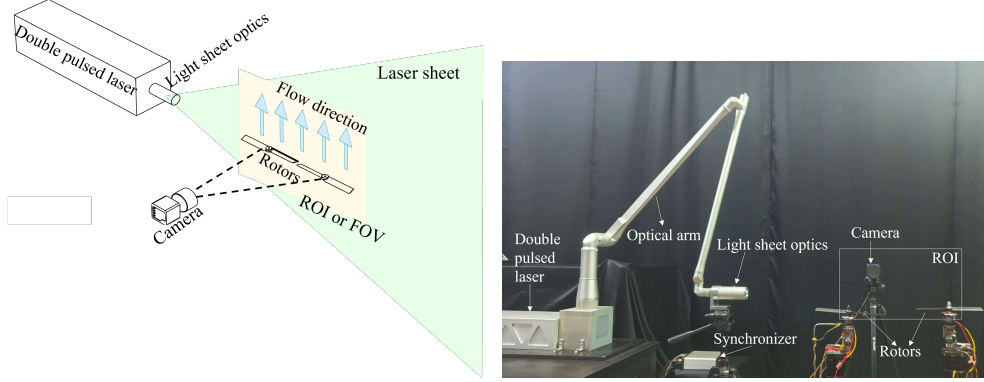


Fig. 2: PIV facility, (left): schematic of the PIV setup; (right): PIV system.

The region of interest or the field of view was chosen to be the overlap region between the rotors. The PIV system was operated in a phase-resolved mode. The phase locking is achieved by triggering the PIV system using a synchronization signal from the downstream rotor, whose span was aligned parallel to the PIV plane (figure 2), corresponding to an azimuthal position of 90° according to rotor nomenclature. The PIV plane was slightly offset from the rotor axis to minimize reflections and shadows. The phase-locking procedure is outlined as follows- since, the rotors were operated at a nominal speed of 5010 RPM, corresponding to 83.5 revolutions per second (rps). Each rotor generated, two pulses per revolution, resulting in a total of 167 pulses per second. These pulses were routed to an Arduino Mega microcontroller, where a digital filtering routine was implemented to allow only one pulse per second to be transmitted. This filtered pulse served as the external trigger for the entire PIV system, thereby ensuring that image acquisition occurred only at the prescribed rotor position.

For the PIV measurements a total of 100 image pairs were acquired. The inter-frame time (Δt) between images in each pair was set to $60\mu\text{s}$, selected based on the expected flow velocities within the measurement region to ensure optimal particle

displacement. Image post-processing was performed using PIVlab [18], employing a cross-correlation algorithm based on the multi-pass FFT window deformation technique. The correlation procedure consisted of three passes, with the interrogation window size progressively reduced from 512×512 pixels in the first pass to 128×128 pixels in the final pass, using a 50% window overlap. Vector validation criteria were applied to restrict the proportion of interpolated vectors to less than 10%. Following vector-field computation in PIVlab, all subsequent post-processing and data analysis were carried out in MATLAB [19].

3 Results and Discussion

3.1 PIV

Phase-resolved PIV measurements were performed to visualize the rotor wake structures and to identify the interaction mechanisms between the upstream and downstream rotor wakes. The results are presented in two stages. First, the wake evolution of a single rotor is analyzed to establish a baseline reference. This is followed by the synchronized tandem rotor cases, where the influence of rotor spacing and relative phase angle on wake interaction mechanisms is examined. Although the inherently three-dimensional wake is captured using 2D-2C PIV, the measurements provide a planar representation that retains the key flow features governing the observed performance variations.

3.1.1 Single rotor

The baseline wake structure for interpreting tandem-rotor interactions is established using single-rotor PIV measurements. Figure 3 shows the wake structure of a single rotor.

The wake is dominated by coherent tip vortices shed from the blade tips, accompanied by weaker vortex sheets originating from the blade surfaces. Tip vortices generated by successive blades of the same rotor exhibit alternating vorticity sense, while the vortex sheet associated with each blade has vorticity opposite to that of its corresponding tip vortex. The tip vortices exhibit significantly larger vorticity magnitudes and remain coherent over several wake ages (ζ), whereas the vortex sheets weaken more rapidly as they convect downstream. The rotor slipstream boundary is also clearly discernible and exhibits radial contraction downstream of the rotor disk, forming a vena-contracta before gradually expanding farther downstream. The vortical structures observed downstream correspond to successive blade passages, separated by $\Delta\zeta = 180^\circ$, and thus represent different wake ages. The vortices closest to the rotor correspond to the most recently formed structures, while those farther downstream originate from earlier wake ages and progressively weaken due to diffusion. By $\zeta = 720^\circ$, the tip vortices exhibit significant loss of coherence, beyond which the wake structures dissipate. Owing to the periodic nature of the rotor flow field, these downstream wake features are representative of the flow structures encountered in subsequent blade passages.

Both the tip vortices and vortex sheets convect downstream, but at different convection velocities. The vortex sheets convect faster than the tip vortices, leading to a progressive separation between these structures as the wake evolves. This behavior is evident across the wake ages shown in figure 3. For instance, the vortex sheet (left side), initially located near the second tip vortex, is observed further downstream to lie below the corresponding vortex, indicating its higher convection speed relative to the tip vortices. A similar trend is observed for the vortex sheet and tip vortices associated with the other blade (right side).

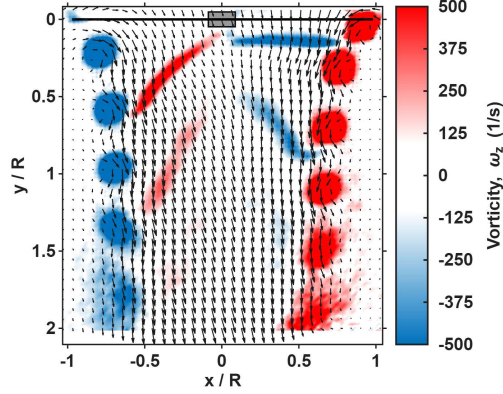


Fig. 3: Ensemble-averaged vorticity field of a single rotor.

At the nominal operating speed of 5010 RPM, the corresponding tip Reynolds number is on the order of 10^5 , placing the flow in a viscous-dominated regime. As a result, the tip vortices are relatively large when normalized by rotor dimensions compared with those observed in full-scale helicopter rotors operating at higher Reynolds numbers. Such large coherent vortical structures can significantly influence wake interactions when multiple rotors operate in close proximity.

These single-rotor measurements establish three key baseline features of the wake: (i) the dominance of coherent tip vortices, (ii) differential convection of vortex sheets relative to tip vortices, and (iii) gradual downstream diffusion of wake structures. These features provide a reference for interpreting the wake interaction mechanisms observed in the tandem rotor configurations discussed in the following sections.

3.1.2 Synchronized tandem rotors

The dominant wake interaction mechanisms in the synchronized tandem-rotor configuration are identified using ensemble-averaged vorticity fields, formed by averaging 100 instantaneous realizations at each test condition. The reference origin $(0, 0)$ is defined at the upstream rotor hub in all the flow-field plots. The test matrix spans six horizontal separations, two vertical separations, and six relative phase angles. For clarity, the discussion separates the cases into non-overlap configurations ($HS = 2.0R$, $2.25R$, and $2.8R$) and overlap configurations ($HS = 1.3R$, $1.5R$, and $1.75R$).

Across the synchronized tandem-rotor cases, three recurring interaction mechanisms are observed depending on rotor spacing and relative phase angle: (i) blade–vortex interaction, in which the upstream rotor tip vortex impinges on or passes very close to the downstream blade; (ii) vortex merging, where wake structures of the same vorticity sense combine into a single coherent structure; and (iii) vortex cancellation or weakening, where interacting structures lose coherence due to destructive interaction. These mechanisms provide a useful framework for interpreting the phase-resolved wake fields presented below.

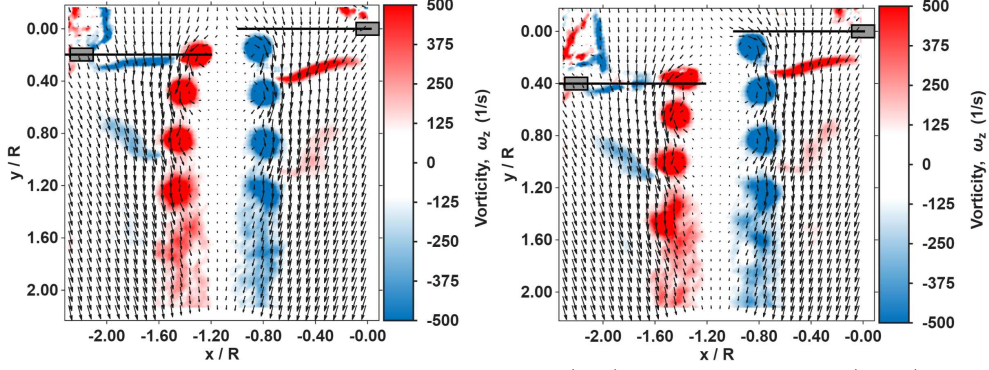


Fig. 4: Ensemble-averaged vorticity field; (left) HS2.25R_VS0.2R; (right) HS2.25R_VS0.4R.

Non-Overlap Cases

For the non-overlap configurations, minimal to no direct wake interaction is observed within the measurement region for horizontal separations exceeding $2R$. Accordingly, only representative fields are shown for selected cases at the two vertical separations. Figure 4 presents the ensemble-averaged vorticity fields for $HS = 2.25R$ at $VS = 0.2R$ and $0.4R$. Tip vortices corresponding to wake ages up to $\zeta = 540^\circ$ retain coherence, whereas vortices from earlier wake ages progressively diffuse downstream. In contrast, only the most recently shed vortex sheet remains coherent and visible. No discernible interaction between the tip vortices of the two rotors is observed for either vertical separation. The vorticity fields for $HS = 2.8R$ were acquired but are not shown, since the absence of wake interaction at $HS = 2.25R$ indicates that the rotors behave effectively as isolated systems at larger separations.

Figure 5 presents the case with $HS = 2.0R$, where the wakes are in closer proximity. Although no direct vortex–vortex interaction is observed in the immediate vicinity of the rotor disks, the vortex trajectories differ from those of the isolated rotor wake. For $VS = 0.2R$, the downstream rotor tip vortices convect approximately straight downstream without the radial contraction and subsequent expansion characteristic of an isolated rotor slipstream, while the upstream rotor tip vortices are drawn toward the downstream rotor axis. For $VS = 0.4R$, both rotor wakes follow nearly straight trajectories, again without the contraction and expansion observed for the single rotor.

Thus, even in the absence of direct interaction, the neighboring rotor modifies the local induced velocity field and alters wake convection.

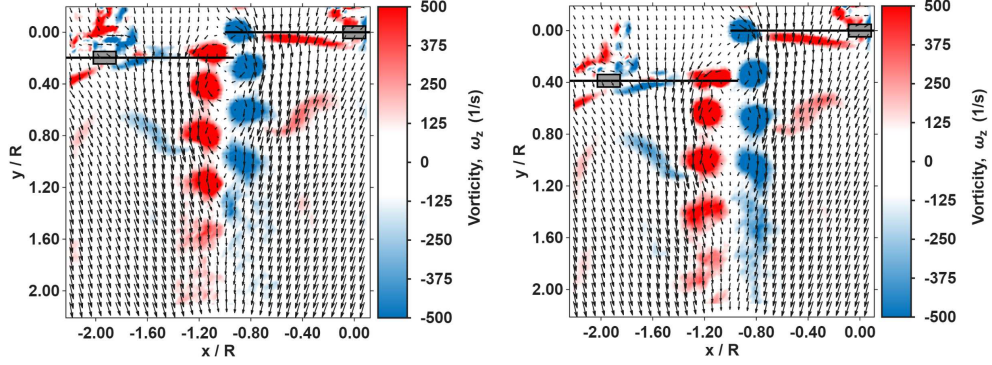


Fig. 5: Ensemble-averaged vorticity field; (left) HS2R_VS0.2R; (right) HS2R_VS0.4R.

Overlap Cases

HS1.3R_VS0.2R

For the overlap cases, representative phase-resolved fields at 30° phase increments are presented to isolate the effect of relative phase angle while maintaining a common wake-age reference. Figure 6 shows the $HS = 1.3R$, $VS = 0.2R$ configuration. The vorticity field at $\phi = 0^\circ$ is shown in its entirety, while the remaining fields are cropped to highlight the region between the rotor hubs; the cropped region is indicated in the first frame. For all such plots, the downstream rotor remains fixed within the PIV plane, while the upstream rotor is rotated to introduce the phase variation. Consequently, the downstream wake features remain essentially unchanged across the phase-angle frames, with the downstream tip vortex consistently appearing at the blade tip as a newly formed vortex, whereas the upstream rotor wake features shift with phase angle. The wake structures observed farther downstream of the downstream rotor correspond to earlier wake ages and represent the subsequent evolution of the interacting wake.

At this spacing, the interaction is highly phase sensitive. For $\phi = 0^\circ$ and $\phi = 30^\circ$, the upstream rotor vortex sheet interacts with the downstream tip vortex and, in parts of the field, also with the downstream rotor vortex sheet. These interactions lead primarily to vortex merging between structures of the same vorticity sense, while the upstream rotor tip vortex convects past the downstream blade with weak or no direct blade interaction. For $\phi = 60^\circ$, $\phi = 90^\circ$, and $\phi = 120^\circ$, the upstream rotor tip vortex intersects or impinges on the downstream blade, leading to clear blade-vortex interaction and substantial weakening or breakdown of the upstream rotor vortex. At the same time, the upstream rotor vortex sheet interacts with the downstream rotor tip vortex or downstream rotor vortex sheet, producing either merging or partial cancellation depending on the local vorticity arrangement. In contrast, at $\phi = 150^\circ$, the primary wake structures convect downstream with relatively weak mutual interaction. Thus, varying the phase angle shifts the relative position of the upstream rotor tip

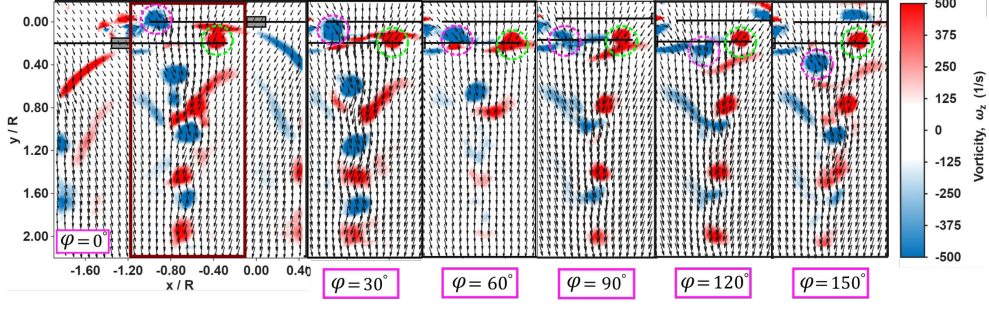


Fig. 6: Ensemble-averaged vorticity field for HS1.3R_VS0.2R for all phase angles ($\phi = 0^\circ$ – 150°).

vortex and vortex sheet with respect to the downstream blade and wake, thereby governing whether the interaction manifests as blade–vortex interaction, vortex merging, and comparatively smooth downstream convection.

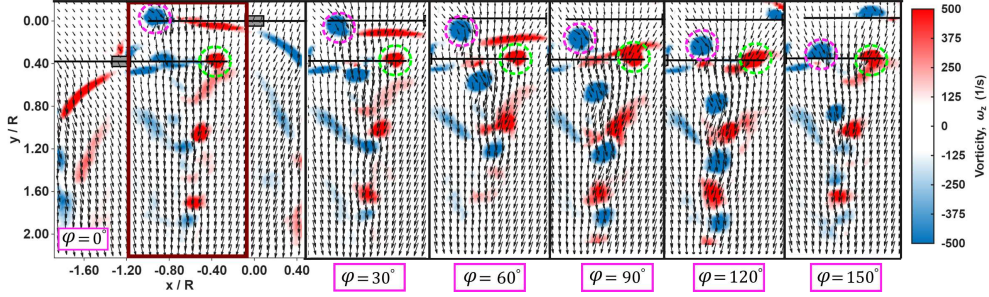


Fig. 7: Ensemble-averaged vorticity field for HS1.3R_VS0.4R for all phase angles ($\phi = 0^\circ$ – 150°).

HS1.3R_VS0.4R

Figure 7 compares the ensemble-averaged fields for $HS = 1.3R$ and $VS = 0.4R$ across all phase angles. Increasing the vertical separation allows the upstream rotor tip vortex and vortex sheet additional time to convect and evolve before encountering the downstream rotor and its wake. As a result, the interaction remains strongly phase dependent, but its character differs from that of the $VS = 0.2R$ case.

For $\phi = 0^\circ$, $\phi = 30^\circ$, and $\phi = 150^\circ$, the upstream rotor tip vortex approaches or directly interacts with the downstream blade, but the interaction occurs after additional wake evolution and therefore tends to be weaker or more spatially distributed than at the smaller vertical separation. For $\phi = 60^\circ$, $\phi = 90^\circ$, and $\phi = 120^\circ$, the dominant interaction shifts toward the upstream rotor vortex sheet and the downstream tip vortex, which merge into a combined structure of the same vorticity sense and remain coherent for a finite downstream distance. A weak positive-vorticity structure is also visible beneath the downstream blade in several of these cases and appears to

originate from the upstream rotor vortex sheet. Overall, the larger vertical separation weakens the most severe direct interactions and promotes smoother downstream convection of the interacting structures.

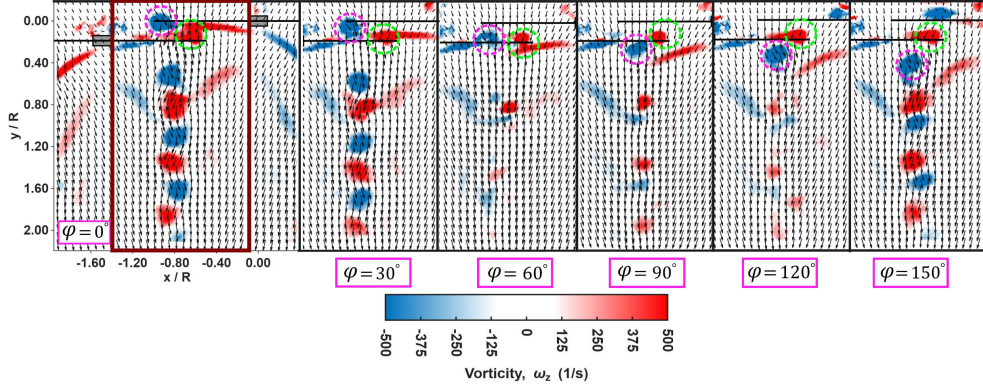


Fig. 8: Ensemble-averaged vorticity field for HS1.5R_VS0.2R for all phase angles ($\phi = 0^\circ$ – 150°).

HS1.5R_VS0.2R

Figure 8 shows the fields for $HS = 1.5R$ and $VS = 0.2R$. Relative to the $HS = 1.3R$ case, the larger horizontal separation shifts the blade-to-vortex encounter location while bringing the tip vortices of the two rotors into closer proximity. The interaction remains strongly phase dependent, but the balance between blade–vortex interaction and vortex–vortex interaction changes.

For $\phi = 0^\circ$ and $\phi = 30^\circ$, the dominant interaction again involves the upstream rotor vortex sheet and the downstream tip vortex, which merge into a combined structure that convects downstream and gradually diffuses. For $\phi = 60^\circ$, the upstream rotor tip vortex impinges directly on the downstream blade and is no longer identifiable farther downstream, indicating strong blade–vortex interaction and substantial vortex breakdown. At the same time, the upstream rotor vortex sheet interacts with the lower portion of the downstream tip vortex, and both structures weaken significantly, suggesting partial cancellation. For $\phi = 90^\circ$ and $\phi = 120^\circ$, the upstream rotor tip vortex also interacts with the downstream blade and loses substantial strength, while the remnants of the upstream rotor vortex and vortex sheet become faint farther downstream. In contrast, at $\phi = 150^\circ$, the upstream rotor tip vortex avoids direct blade interaction and the downstream tip vortex does not interact strongly with the upstream rotor vortex sheet, so both structures remain comparatively strong and identifiable downstream.

HS1.5R_VS0.4R

Figure 9 shows the corresponding fields for $HS = 1.5R$ and $VS = 0.4R$. The overall behavior resembles that of the $HS = 1.3R$, $VS = 0.4R$ case, with the main difference being the closer proximity of the tip vortices. For $\phi = 150^\circ$, $\phi = 0^\circ$, and $\phi = 30^\circ$, the upstream rotor tip vortex interacts directly with the downstream blade,

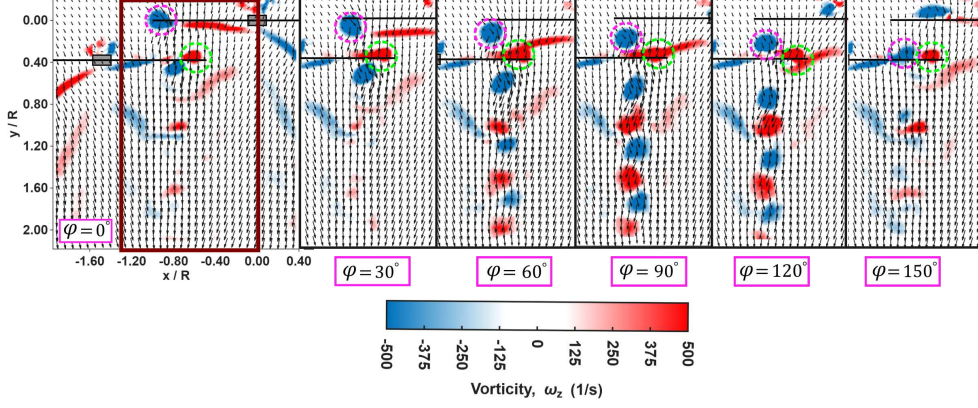


Fig. 9: Ensemble-averaged vorticity field for HS1.5R_VS0.4R for all phase angles ($\phi = 0^\circ$ – 150°).

and the downstream wake subsequently shows substantial weakening or near-complete cancellation of coherent structures. For $\phi = 60^\circ$, $\phi = 90^\circ$, and $\phi = 120^\circ$, the upstream rotor tip vortex does not encounter the downstream blade. Instead, the dominant interaction occurs between the downstream tip vortex and the upstream rotor vortex sheet, and the downstream wake remains more coherent. Thus, as in the smaller-overlap case, the phase angle determines whether blade–vortex impingement or milder vortex–vortex interaction dominates the wake dynamics.

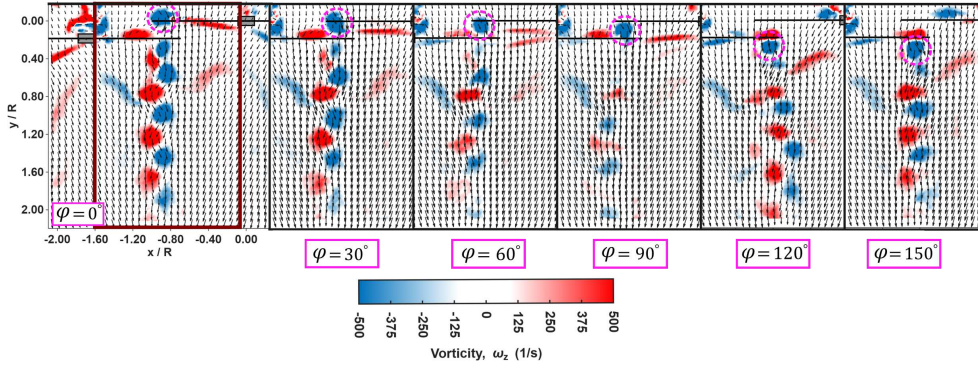


Fig. 10: Ensemble-averaged vorticity field for HS1.75R_VS0.2R for all phase angles ($\phi = 0^\circ$ – 150°).

HS1.75R_VS0.2R

Figure 10 shows the fields for $HS = 1.75R$ and $VS = 0.2R$. At this spacing, the phase-dependent interaction differs from that observed at other overlaps due to the reduced distance between the rotors, which brings the tip vortices into much closer proximity than in the previous cases. For $\phi = 0^\circ$ and $\phi = 30^\circ$, the wake fields are very similar:

coherent vortical structures from successive shedding events convect downstream along nearly straight trajectories. In these cases, the upstream rotor tip vortex does not interact strongly with either the downstream blade or the nearby wake structures. For $\phi = 60^\circ$ and $\phi = 90^\circ$, stronger interaction occurs, leading to partial cancellation and noticeable weakening of the downstream wake; the remaining faint structures deflect toward the downstream rotor axis. For $\phi = 120^\circ$ and $\phi = 150^\circ$, the upstream rotor tip vortex has largely convected past the downstream rotor, and the downstream wake again remains relatively coherent, indicating weaker interaction between the primary vortical structures.

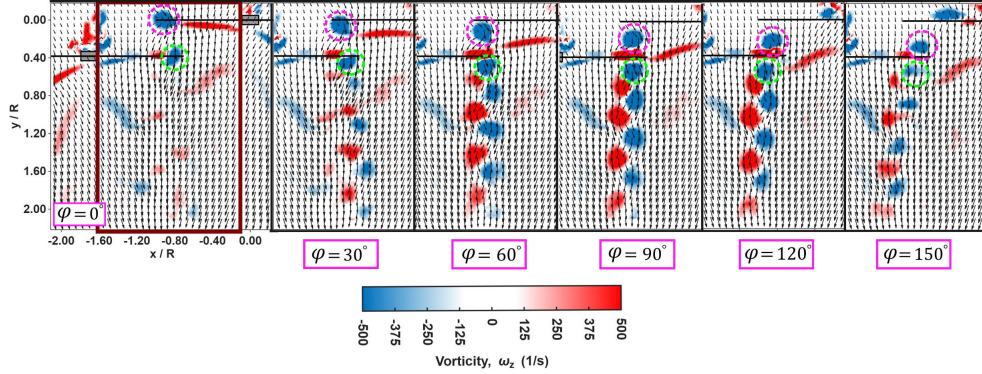


Fig. 11: Ensemble-averaged vorticity field for HS1.75R_VS0.4R for all phase angles ($\phi = 0^\circ$ – 150°).

HS1.75R_VS0.4R

Figure 11 shows the case with $HS = 1.75R$ and $VS = 0.4R$. The interaction remains phase dependent. At $\phi = 0^\circ$, the upstream rotor and downstream tip vortices interact near the downstream blade tip and undergo almost complete cancellation, leaving little coherent wake structure farther downstream. At $\phi = 30^\circ$, the interaction remains strong, although some weakened vortical structures persist. In contrast, for $\phi = 60^\circ$, $\phi = 90^\circ$, and $\phi = 120^\circ$, the interaction is comparatively weak and well-defined vortical structures remain visible downstream of the rotor. For several phases, particularly $\phi = 120^\circ$ and $\phi = 150^\circ$, the wake deflects toward the downstream rotor axis, indicating persistent modification of the local induced flow even when strong vortex breakdown does not occur. At $\phi = 150^\circ$, this wake deflection is accompanied by appreciable interaction between the upstream rotor and downstream tip vortices, which reduces the wake strength farther downstream.

Overall, the PIV measurements show that synchronized tandem-rotor wake interaction depends on both rotor spacing and relative phase angle. In the non-overlap configurations, the dominant effect is a change in vortex trajectory without direct vortex–vortex interaction. In the overlap configurations, blade–vortex interaction, vortex merging, and vortex cancellation dominate, and their relative importance depends strongly on phase angle and vertical separation. Increasing the vertical separation gives

the wake more time to evolve before interaction and therefore weakens the strongest direct encounters. These phase-dependent wake interactions are expected to modify the aerodynamic loading on the downstream rotor and are reflected directly in the thrust and torque measurements discussed in the following section.

3.2 Performance measurements

3.2.1 Vertical Separation of 0.2R

Figure 12 shows the performance characteristics of the upstream rotor and downstream rotors for all phase angles and horizontal separations at a fixed vertical separation of 0.2R. The performance is quantified using the non-dimensional thrust and power coefficients, C_T and C_P , respectively. Figure 12 (a) illustrate the variations of C_T for the downstream rotor. For the non-overlapping configurations (HS2.8R, HS2.25R, and HS2R), the thrust coefficient remains nearly unchanged as the horizontal separation decreases. Since the rotor disks do not overlap, the upstream rotor wake does not significantly influence the downstream rotor, resulting in negligible aerodynamic interaction and minimal variation in performance. A clear reduction in C_T occurs with increasing rotor overlap, with the lowest value observed for HS1.3R. This trend arises because increased overlap causes a larger portion of the downstream rotor blades to operate within the upstream rotor wake, increasing the inflow angle and reducing the effective angle of attack.

For non-overlapping configurations, C_T shows negligible dependence on phase angle, with all cases clustering around $C_T \approx 0.016$. This indicates that phase-dependent aerodynamic interaction remains weak when the rotor separation is sufficiently large. In contrast, overlapping configurations exhibit a clear phase-angle dependence.

For HS1.75R, C_T increases with phase angle, reaches a maximum at $\phi = 90^\circ$ (approximately 0.0157), and then decreases to a minimum at $\phi = 0^\circ$ (approximately 0.0152). As the overlap increases to HS1.5R, the phase sensitivity becomes more pronounced while maintaining a similar trend. The maximum shifts to $\phi = 60^\circ$ (approximately 0.0152), while the minimum occurs at $\phi = 0^\circ$ and $\phi = 150^\circ$ (approximately 0.0145). For HS1.3R, the variation is strongest: C_T increases from $\phi = 0^\circ$ to a maximum at $\phi = 30^\circ$ (approximately 0.0145), followed by a gradual decrease up to $\phi = 120^\circ$ and a sharper drop at $\phi = 150^\circ$ (approximately 0.0135), corresponding to a peak-to-peak variation of about 0.001.

Overall, increasing rotor overlap reduces the mean C_T and increases its sensitivity to phase angle. This behavior is governed by the interaction between upstream rotor wake structures and the downstream rotor blades.

The variation in C_T can be interpreted using the wake interaction patterns shown in figure 6. At $\phi = 0^\circ$ and $\phi = 150^\circ$, the upstream rotor wake (tip vortex and vortex sheet) convects past the downstream rotor without significant blade interaction, resulting in the lowest C_T . At intermediate phase angles, both the upstream rotor tip vortex and vortex sheet interact with the downstream blades to varying degrees, producing the observed variation in thrust.

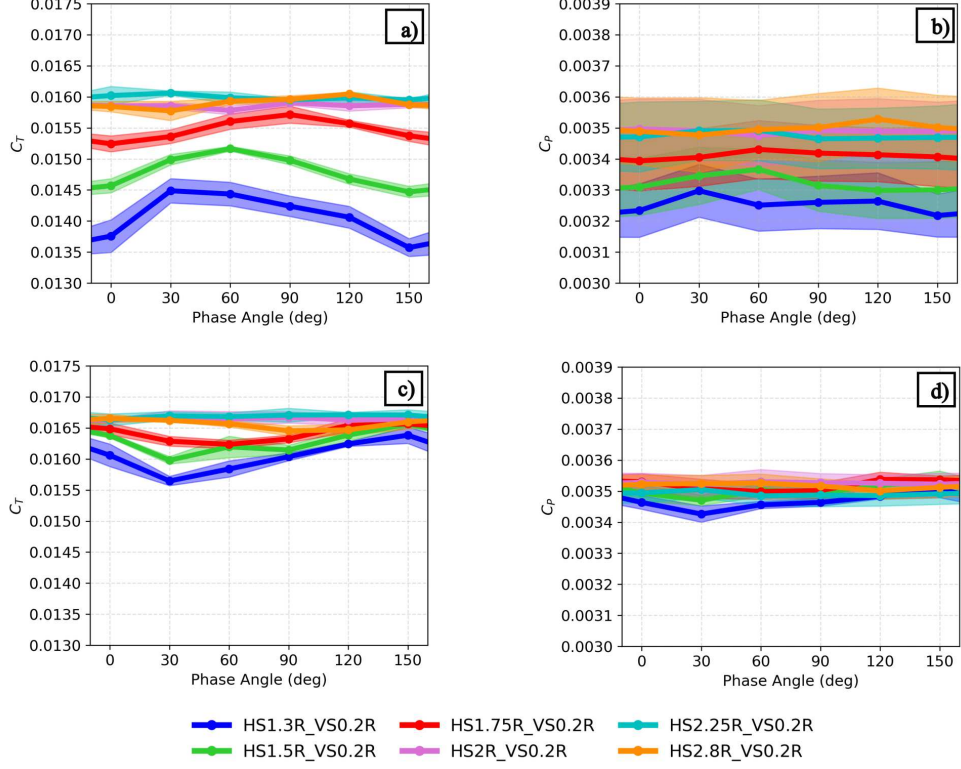


Fig. 12: Performance plots for VS0.2R at all phase angles and with varying HS; (a): downstream rotor C_T , (b): downstream rotor C_P , (c): upstream rotor C_T , and (d): upstream rotor C_P .

At $\phi = 30^\circ$, the upstream rotor tip vortex lies above the downstream blade while the upstream rotor vortex sheet remains just below it, producing the highest C_T . At $\phi = 60^\circ$, the tip vortex convects onto the rotor disk and the vortex sheet shifts downward, leading to a slight reduction in thrust. At $\phi = 90^\circ$, stronger interaction leads to partial dissipation of the vortex, while the vortex sheet convects further downward, reducing C_T further. By $\phi = 120^\circ$, both structures lie below the blade, resulting in minimal interaction and reduced thrust.

This behavior is consistent across all overlap configurations for VS0.2R. Higher thrust occurs when the upstream rotor tip vortex lies above the blade, and the vortex sheet remains below it. When these structures are located further down with respect to the downstream blade, their influence is weaker, and C_T is lower. These observations indicate that thrust variation depends on the combined influence of both the tip vortex and vortex sheet.

The rotor overlap also determines the radial and azimuthal location of interaction along the downstream rotor. This is observed as a shift in the phase angle corresponding to maximum C_T across different overlaps. For HS1.3R, the upstream rotor vortex

is relatively distant from the downstream tip vortex, whereas increased overlap brings the vortices closer and weakens their influence on blade loading.

The upstream rotor tip vortex influences the downstream blade through its low-pressure core. When this low-pressure region interacts with the blade's suction side, it enhances the local pressure difference, thereby increasing thrust. When the vortex moves toward the pressure side of the downstream blade, this pressure difference augmentation diminishes, resulting in reduced thrust.

Figure 12 (b) shows the variation of C_P for the downstream rotor. The power coefficient decreases with increasing overlap, broadly following the trend of C_T . However, the dependence of C_P on phase angle is weak for all configurations, indicating that phase-dependent wake interaction has limited influence on overall power consumption.

Although C_P follows the trend of C_T , the correspondence is not exact. Since total power consists of induced, profile, and interaction losses, deviations from proportionality indicate the contribution of additional loss mechanisms. In particular, wake-blade interactions modify local flow conditions and increase profile and interaction losses. For larger separations, where wake interaction is weak, C_P remains nearly invariant with phase.

Figure 12 (c) and (d) illustrates the upstream rotor performance. The variation in C_T with horizontal separation is significantly smaller than that of the downstream rotor. The upstream rotor varies by only about 0.0007 across the range of separations, compared to 0.002 for the downstream rotor.

For HS1.3R and HS1.5R, a phase dependence is observed. The minimum C_T occurs at $\phi = 30^\circ$ and increases toward $\phi = 150^\circ$. This trend is opposite to that of the downstream rotor. Unlike the downstream case, the phase corresponding to minimum C_T does not shift with separation. For HS1.75R, phase dependence is negligible. The variation in C_P for the upstream rotor remains weak across all cases.

The weak sensitivity of the upstream rotor arises from indirect interaction with the downstream rotor. Since the downstream wake does not propagate upstream, the interaction occurs through modification of the downstream pressure field. The downstream rotor creates a low-pressure region below the upstream rotor, effectively reducing the pressure difference across it, resulting in slightly lower thrust. Thus, changes in downstream rotor performance indirectly influence the upstream rotor performance.

3.2.2 Vertical Separation of 0.4R

Figure 13 shows the performance at a vertical separation of $0.4R$. Figure 13(a–b) illustrate the downstream rotor performance, while figure 13(c–d) correspond to the upstream rotor. The variation of C_T with overlap follows trends similar to those observed for VS0.2R.

For non-overlapping configurations, C_T remains in the range 0.0161–0.0163 with no dependence on phase or separation. As overlap increases, C_T decreases, reaching approximately 0.0135 for HS1.3R. For HS1.3R, the phase dependence remains but shifts: the minimum occurs at $\phi = 0^\circ$, and the maximum shifts by $+30^\circ$. The variation is smaller than for VS0.2R, indicating reduced sensitivity to phase. For HS1.5R and HS1.75R, phase dependence is minimal.

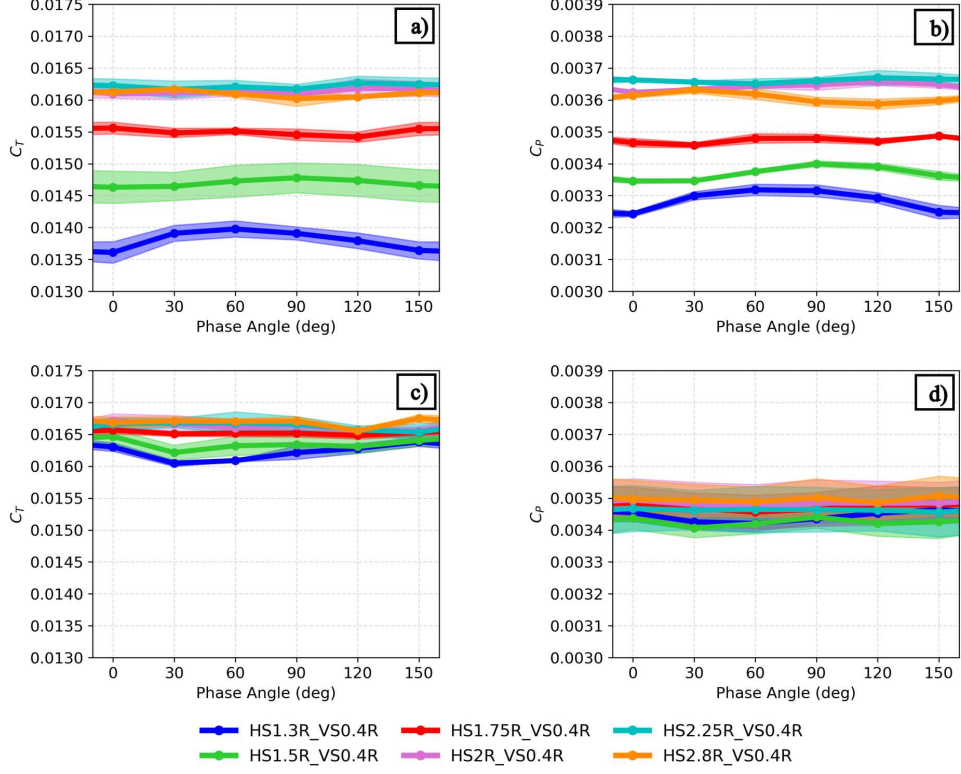


Fig. 13: Performance plots for VS0.4R at all phase angles and with varying HS; (a): downstream rotor C_T , (b): downstream rotor C_P , (c): upstream rotor C_T , and (d): upstream rotor C_P .

The wake interaction patterns observed in Figs. 9–11 explain this behavior. Increased vertical separation allows the upstream rotor wake more time to evolve before interacting with the downstream rotor. As a result, the tip vortex diffuses and its influence becomes spatially distributed rather than concentrated. Consequently, strong localized blade–vortex interactions are reduced.

The vortex trajectory also contracts radially during convection, shifting the interaction region radially outward and reducing the portion of the upstream rotor wake ingested by the downstream rotor. These effects weaken wake–blade interaction, reduce phase sensitivity, and shift the phase angle corresponding to maximum C_T .

Despite these changes, the underlying interaction mechanism remains the same. Maximum thrust occurs when the upstream rotor tip vortex lies above the blade and the vortex sheet lies below it. When these structures are further down, their influence and the C_T reduce for the corresponding phase angles.

The variation in C_P follows the same trend as C_T , indicating that induced power remains dominant. Increased vertical separation reduces wake interaction losses, as reflected by the smoother C_P curves.

The upstream rotor shows even weaker sensitivity for VS0.4R compared to VS0.2R. Since the downstream rotor itself exhibits reduced phase variation, the induced pressure field affecting the upstream rotor is also weaker. Consequently, variations in upstream rotor performance are further reduced.

4 Conclusion

This study demonstrates a direct coupling between wake interaction mechanisms and aerodynamic performance in low-Reynolds-number tandem rotors using phase-locked experiments across a range of horizontal and vertical separations. By combining phase-resolved PIV with thrust and torque measurements, the wake structures responsible for performance variations are identified explicitly.

The results establish that the relative phase angle acts as an additional governing parameter, alongside horizontal and vertical separation. Changing the phase angle shifts the position of the upstream rotor tip vortex and vortex sheet relative to the downstream blade, thereby altering both the interaction mechanism and its strength. Depending on rotor spacing, the interaction transitions between blade–vortex interaction, vortex merging, and weakly coupled convection, with corresponding changes in rotor performance.

The main implications are as follows.

1. *Single rotor.*

The baseline wake consists of coherent tip vortices, weaker vortex sheets, and a contracting slipstream characteristic of low-Reynolds-number operation. At $Re \sim 10^5$, viscous effects produce relatively large normalized vortex cores, which play a central role in subsequent rotor–wake interactions.

2. *Non-overlap configurations.*

For $HS \geq 2R$, the wakes remain largely separated and do not exhibit strong vortex–vortex interaction. The vortex trajectories nevertheless deviate from the isolated rotor case, indicating modification of the local induced flow. Under these conditions, wake interaction remains weak and the thrust and power coefficients show negligible dependence on phase angle.

3. *Overlap configurations.*

For $HS = 1.3R$ – $1.75R$, strong interaction occurs between the upstream rotor wake and the downstream rotor. The phase angle controls the blade-to-wake encounter, governing whether the interaction manifests as blade–vortex interaction, vortex merging, and weak interaction. These interaction modes map directly to the measured performance.

The downstream rotor shows the strongest phase sensitivity, particularly at higher overlap, with the largest thrust variation observed for $HS = 1.3R$. In contrast, the upstream rotor remains comparatively insensitive, indicating predominantly one-way coupling from the upstream rotor wake to the downstream rotor.

Higher downstream thrust occurs when the upstream rotor tip vortex lies above the blade while the vortex sheet remains below it, enhancing blade loading. As these structures convect downward, their influence weakens and thrust decreases.

The phase angle corresponding to peak thrust shifts with overlap, consistent with the change in interaction location observed in the PIV measurements.

4. *Effect of vertical separation.*

Increasing the vertical separation from $0.2R$ to $0.4R$ allows additional wake evolution before interaction. The upstream rotor wake becomes more diffuse, reducing the intensity and frequency of blade–vortex interaction. This weakens rotor–wake coupling and reduces phase sensitivity in the performance.

Overall, tandem-rotor performance at low Reynolds number is governed not only by rotor spacing but also by the relative phase angle, which determines how the upstream rotor wake interacts with the downstream rotor. Phase effects remain weak for separated wakes but become dominant in overlapping configurations. Rotor phasing therefore provides a practical additional degree of freedom for controlling wake interaction in compact tandem-rotor systems.

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