

Effect of centerline separation on a vortex dominated wake

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An experimental investigation was conducted on the wake of a rounded-edge slanted afterbody over a Reynolds number range of $Re_D = 40$ K to $Re_D = 200$ K. High-speed particle image velocimetry (PIV), surface pressure measurements, and high-accuracy drag measurements provided substantial insight into this complex flow. In particular, they revealed an undocumented wake-state transition from a previously observed centerline-separated (CS) vortex state to a new centerline-attached (CA) vortex state between $Re_D \approx 130$ K and 180 K. This wake transition was accompanied by a significant drag reduction and the transition of the upstream boundary layer from laminar to turbulent. The CS vortex state shared characteristics with laminar separation bubbles and produced spatially diffuse vortices that exhibited two distinct instabilities: a low-frequency flapping instability that governed the vortex dynamics and a high-frequency short-wave instability that drove shear layer breakdown and reattachment. The reduction in recirculation length was attributed to diminished viscous damping at higher Reynolds numbers, enabling earlier shear layer transition. In contrast, the CA state exhibited neither frequency signature and lacked a separated region, indicating a fundamentally different underlying dynamical mechanism. The vortices in the CA state were highly structured and spatially coherent, further distinguishing them from the diffuse and unsteady vortices observed in the CS state. These results provide new physical insight into the interplay between upstream boundary-layer transition, separated shear layer dynamics, wake topology, and their collective effect on global aerodynamics in terms of drag. Together, they provide a more comprehensive and unified understanding of the wake states and their transition between CS and CA for bluff body wakes.

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I. INTRODUCTION

The slanted afterbody is a three-dimensional bluff body that has been studied due to its unique wake dynamics and flow separation characteristics. This geometry, shown in Fig. 1, consists of a primary cylindrical midbody, a forebody with an elliptic nose, and an afterbody that concludes with a sharp angled slice. Recent efforts have used this configuration to study the wake effects of cargo aircraft, due to the afterbody geometric and wake similarities with the wide tail geometry [1–10]. In addition to cargo aircraft, the general geometry of the slanted afterbody has extended its

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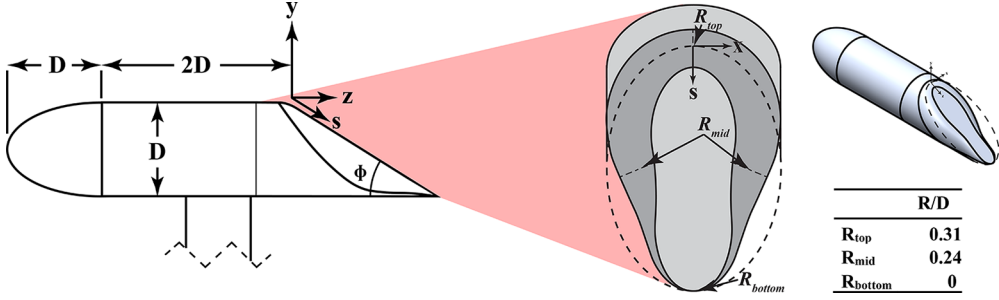


FIG. 1. Schematic of the slanted afterbody geometry depicting the radius dimensions and coordinate system.

application to high-speed trains [11], has particular similarities with automobile rear window slants, and canonically resembles avian afterbodies.

This afterbody, with its large slant and wide aft geometry, produces a highly turbulent, three-dimensional wake dominated by two counterrotating vortices. These vortices exhibit significant unsteadiness, ranging from low-frequency meandering to higher-frequency turbulence-driven fluctuations. In the context of cargo aircraft, the vortices produce negative aerodynamic effects such as added drag, negative lift [12], altered cargo drop accuracy, and hazards to paratroopers exiting the aircraft.

This bluff body geometry is of particular interest, as it has been identified by Morel [13] as belonging to a larger class of bluff bodies known as ‘critical geometries,’ a geometry where slight parameter changes lead to a drastic flow transition. Morel [13] identified one such transition between two distinct wake regimes: a low-drag, fully separated wake state, and a high-drag, centerline-separated (CS) vortex state. Morel [13] found this transition to be governed by changes in the slant angle with a critical angle of $\phi = 45^\circ$. Later work found this same transition to be hysteretic in nature and dependent on Reynolds number and Mach number [6,7,9,10,14,15]. It is important to emphasize that, in all studies of the slanted afterbody, transitions observed for the sharp-edge geometry have consistently occurred only between two wake states: the fully separated wake state and the centerline-separated (CS) vortex state.

The fully separated wake is characterized by flow separation on the sharp edges of the afterbody. At the leading edge, the flow forms a free shear layer that does not reattach on the model surface. Within the afterbody wake, the flow is divided into two regimes: a lower half that is dominated by a recirculation region and a top half dominated by toroidal vortices. This flow state is defined in detail by Zigunov *et al.* [7], but is not the main topic of discussion due to the infrequency of this state within real-world applications [16,17].

The CS vortex state is, again, characterized by flow separation on the sharp edges of the afterbody. However, the free shear layer formed at the leading edge reattaches downstream on the model afterbody, enclosing a region of recirculation. The point of reattachment on the model’s surface is referred to as the ‘source point’ [7]. Additionally, the flow that separates on the sides of the model forms a free shear layer that rolls into the distinctive longitudinal counterrotating vortices that dominate the afterbody wake. It is crucial to note that there is a continuous connection between the vortices through the recirculation region, forming a horseshoe shape of vorticity/circulation.

A key similarity between these wake states is that, in both cases, the sharp leading edge of the afterbody forces flow separation. Although useful as a building block canonical problem from a fundamental perspective, these edges do not accurately represent real-world configurations, which feature smooth or rounded edges. Compared to sharp-edge models, rounded edges can enable the flow to remain attached at the afterbody leading edge, altering the separation dynamics [16–18]. Separation on sharp edges is known to inhibit the development of unsteady

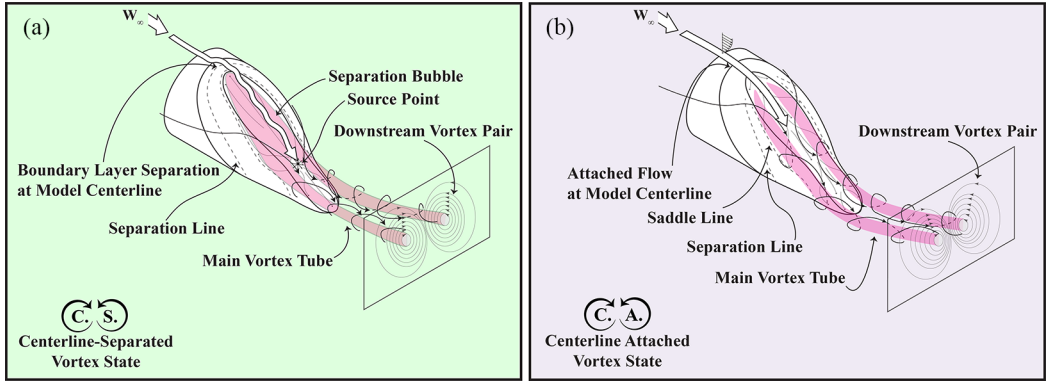


FIG. 2. Illustration of the flow regimes produced by the rounded-edge afterbody as modified from Huss *et al.* [9]. The centerline separated (CS) vortex state is shown in (a), and the centerline attached (CA) vortex state is shown in (b).

features that are associated with a flexible separation locus produced by free-boundary layer separation [18,19].

Recent work has explored a modified, rounded-edge slanted afterbody geometry, which is intended to mimic the rounded edges of cargo aircraft afterbodies [9,10,20]. These studies have identified drastic variations in the dynamics of the CS vortex state, including a significant increase in recirculation region size, reduction in drag, and a change in the unsteady dynamics of the vortices. Additionally, Huss *et al.* [9] identified a new flow state, the centerline attached (CA) vortex state, which is characterized by the absence of a centerline recirculation region and a lack of flow separation at the afterbody leading edge.

To provide a depiction of the three-dimensionality of the wakefields and a comparison between them, a descriptive illustration is provided in Fig. 2. Figure 2(a) describes the CS vortex state and highlights the centerline boundary layer separation, formation of the free shear layer, and reattachment at the source point closing in the recirculation region. Figure 2(b) describes the CA vortex state and clearly illustrates centerline attached flow and absence of the recirculation region as described by Huss *et al.* [9]. In both cases, vortices originate from boundary-layer separation along the model sides, producing shear layers that subsequently roll up into coherent vortical structures in the wake. However, for the CS vortex state, the vortices are connected through the centerline recirculation region, forming a horseshoe-like structure, whereas in the CA vortex state, the vortices are disconnected. In both figures, the pink surfaces refer to regions of recirculating flow, i.e., the vortices and/or the centerline recirculation region (often referred to as the separation bubble in literature regarding this flow [7]). While these surfaces contain vorticity, the surface does not solely refer to regions of vorticity. This distinction is important as vorticity persists in the CA state through the centerline boundary layer; however, separation and a corresponding recirculating region/separation bubble are not present. More details regarding the fundamental properties of the three-dimensional flow field and the different vortex states can be found in Huss *et al.* [10], Zigunov *et al.* [7], and Huss *et al.* [9].

This work first identifies a previously undocumented Reynolds-number-dependent transition between the centerline-separated (CS) and centerline-attached (CA) vortex states for the rounded-edge slanted afterbody geometry and characterizes the associated wake flow features. The underlying mechanism governing this transition is then examined by carefully analyzing the centerline flow characteristics and unsteady dynamics. Finally, the influence of centerline separation or attachment on the downstream vortex structure and unsteady behavior is explored. These findings provide new physical insight into bluff body wakes and highlight the critical role of edge geometry in determining wake and vortex behavior.

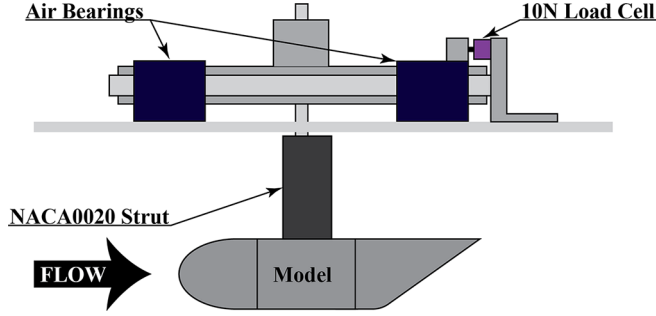


FIG. 3. Slanted afterbody mounted in the FCAAP LSWT. The low-drag instrument is pictured on top of the test section.

II. EXPERIMENTAL SETUP

A. Facility and model details

All experiments were performed in the low-speed wind tunnel (LSWT) at the Florida Center for Advanced Aero-Propulsion (FCAAP). The LSWT is a subsonic Eiffel-type wind tunnel capable of providing flow speeds from 2.4 m/s to 70 m/s. The test section is 30 in $\times$ 30 in square by 60 in long, and free-stream turbulence levels have been measured to be less than 0.3% [21]. Optical windows are provided on all sides of the test section to allow ease of optical access.

The slanted afterbody model, seen in Fig. 1, is comprised of an elliptical nosecone with a 2:1:1 ratio, a cylindrical midbody, and an afterbody with slant angle ϕ . The diameter of the model is 5.75 in or 146.05 mm, and two different model slant angles were used, $\phi = 32^\circ$ and $\phi = 45^\circ$. The afterbody was rounded using a linear variable edge fillet that applied a radius in four different locations on the slanted afterbody face as described in Fig. 1. The model was attached to a NACA0020 airfoil strut with a thickness of $t = 22$ mm and was positioned on the side opposite the afterbody leading edge. This location has been tested and proven to negligibly impact the flow field [22]. Figure 1 also displays the coordinate system used, in which x is the spanwise coordinate, y is the vertical coordinate, z is the streamwise coordinate, and s is the coordinate tangent to the slanted surface along the model centerline, with the origin located at the leading sharp edge or virtual crossing point of the two straight surfaces.

As described, rounded-edge afterbody models were examined with two varied slant angles, $\phi = 32^\circ$ and $\phi = 45^\circ$. Apart from these two models, two sharp-edge models of the same slant angles were also tested for drag measurements and verification of the low-drag instrument accuracy/repeatability. The authors would like to note that the sharp-edge dynamics are not the primary focus of this study and will only be referenced as a baseline comparison.

The data collected in this study span a Reynolds number range from $Re_D = 15$ K to $Re_D = 400$ K for both rounded-edge models. Four Reynolds numbers within the targeted transition regime— $Re_D = 40$ K, $Re_D = 120$ K, $Re_D = 150$ K, and $Re_D = 190$ K—were selected for detailed analysis. The discussion primarily focuses on the $\phi = 32^\circ$ model due to redundancy in the $\phi = 45^\circ$ model results; however, the $\phi = 45^\circ$ model results are included where appropriate, and a summary of test conditions and important parameters is provided in Tables I and II.

B. High-resolution low-drag measurements

Drag measurements were performed using an in-house designed and built low-drag instrument, as seen in Fig. 3. The drag instrument, made from Al6061, consists of a solid chassis that houses the model. The chassis is connected to four NewWay S303801 1.5 in air bushings. Each air bushing is capable of supporting up to 145 lbs radially and linearly slides frictionless on the inserted shaft. The chassis and model are positioned parallel to the freestream direction such that all motion and

measured forces are in the streamwise direction, i.e., solely drag forces are measured. An Omega LCMFD-10 N load cell or LCMFD-50 N load cell (0.15%FSO accuracy), dependent on the expected load, was positioned such that all motion impinges on the load cell. This setup allows one-directional force to be directly measured by the load cell with high accuracy and without consideration of friction forces.

Load cell measurements were recorded at a frequency of 1 kHz over 20 seconds. The load cell signal was passed through an MX9000 amplifier box with a gain of 100 before being read into the DAQ system. It is important to note that this setup is highly affected by electrical noise, including but not limited to EMF from the tunnel fan. To provide higher-order accuracy, the entire system was floated through isolation transformers, such that the drag instrument does not share any ground or system connections with the tunnel fan or respective variable frequency drive.

The force measured directly by the load cell does not immediately represent the true drag on the slanted afterbody and requires further correction. Two identified sources of systematic error are accounted for: the added drag due to the strut, and tunnel blockage. To mitigate the additional drag due to the presence of the strut, separate tests were conducted measuring the force produced by a lone, identical strut. These values were then subtracted from the raw force value. Additionally, solid and wake blockage of both the afterbody and strut were corrected for utilizing the drag correction processes outlined within Barlow *et al.* [23].

To further improve accuracy in calculations of the dynamic pressure which is used within drag coefficient calculations ($C_D = \frac{F_D}{\rho_d A}$), various pressure transducers were used in tandem with the tunnel pitot-static probe for various flow speeds: Setra 339H (1 psid) transducer for flow speeds greater than 20 m/s, PX663-1BD5V (+/- 1 inWC) transducer for flow speeds below 20 mps but above 6.4 m/s, and PX663-0.1D5V (0.1 inWC) transducer for flow speeds below 6.4 m/s. Drag coefficient uncertainties were calculated with consideration of both the load cell and pressure transducer accuracies, as well as error in the blockage calculations. These are reflected as uncertainty/error bars in the relevant plots.

C. Steady pressure measurements

To provide a description of the pressure profile on the model surface and to identify the structures associated with pressure drag, steady pressure taps were aligned along the model centerline. Due to the curvature of the model, the pressure tap locations varied within the streamwise direction and between models/slant angles. Streamwise pressure locations are provided in corresponding C_p plots (Fig. 9). The pressure taps were connected to a 16-channel Scanivalve DSA-5000 differential pressure scanner (10 in.H₂O range, 0.15% FSO accuracy). All pressure measurements referenced the tunnel static pressure as collected through the tunnel pitot-static probe. Pressure measurements were recorded and averaged over a duration of 20 seconds and a frequency of 500 Hz.

D. High-speed PIV

Two methods of high-speed particle image velocimetry (PIV) were utilized, employing a total of three setups: two planar PIV setups—a whole-field measurement and a focused near-field/boundary layer measurement—and one whole-field stereo PIV setup. All setups used a Photonics DM60-532-DH double-pulsed 532nm NdYag laser with an image acquisition rate of 5kHz. At these flow speeds, 5 kHz is higher than necessary to capture the low-frequency structures hypothesized to be associated with vortex meandering by Huss *et al.* [24]. However, this is the lowest repetition rate available for the laser. All setups used identical Phantom v2012 cameras with a resolution of 1280 × 800 pixels and Davis 8.4 software to process the instantaneous vector fields. A double-sided 3-D calibration plate, LaVision Type22, was used to calibrate the cameras for the whole-field planar and stereo PIV measurements. Additional self-calibration refinement was performed for the stereo PIV calibration to further refine the calibration accuracy [25]. The resulting calibrations yielded a scale of 3.42 pix/mm and 6.81 pix/mm for the planar and stereo PIV setups, respectively,

with calibration errors of 0.11 pix and 0.17 pix. Near-field/focused boundary layer planar PIV measurements used a LaVision Type106-10 calibration plate. The resulting calibration yielded a scale of 10.48 pix/mm with a calibration error of 0.14 pix. 10,000 total vector fields were recorded. All mean vector calculations were performed over a subset of 1000 instantaneous fields within the total, and second-order/spectral analyses were performed over the entire set.

1. Planar PIV

The planar PIV setups positioned the laser beam through a 1000 mm converging spherical lens and a -50 mm diverging cylindrical lens such that the laser plane fell on the model centerline. The camera was positioned to observe the laser sheet at a perpendicular angle. The whole-field setup observed the model in its entirety, using a 50 mm lens and 1.4x teleconverter. The second setup targeted the boundary layer prior to the radius, using a 135 mm lens. Both methods were optimized for their specific measurement objectives. Pre- and post-processing of the PIV data was performed using Davis 8.4 software. Raw images were subjected to an average background subtraction, followed by a 16×16 pixel interrogation window with 75% overlap and outlier detection. The calibration and processing yielded a resolution of 0.9 vec/mm for the whole-field measurement and 2.6 vec/mm for the near-field measurement.

Using 1000 image pairs, the whole-field planar PIV velocity measurements witness error as high as 5% of the freestream velocity. The near-field planar PIV velocity measurements witness error as high as 4% of the freestream velocity at a location closest to the wall. These error values were calculated for the lowest velocity case, $Re_D = 40$ K ($W_\infty = 4.19$ m/s), and within regions of high shear, representing the worst-case scenario. The error is significantly lower in the freestream and recirculation regions as well as in higher-velocity cases ($<2\%$ for the $Re_D = 150$ K case).

2. Stereo PIV

The stereo PIV setup used the same lens combination for the laser, but positioned the sheet spanwise to the flow at a location 1D downstream of the model trailing edge. Two cameras were used with identical 105 mm lenses and wide-angle Scheimpflug adapters. The two cameras were positioned on opposite sides of the tunnel, offset approximately 100 degrees from each other. Pre- and post-processing of the PIV data was performed using Davis 8.4 software. Raw images were subjected to an average background subtraction, followed by a 16×16 pixel interrogation window with 75% overlap and outlier detection. The calibration and processing yielded a resolution of 1.7 vec/mm.

Using 1000 image pairs, the stereo PIV velocity measurements witness error as high as 1% of the freestream velocity for the streamwise (out-of-plane) component. This error value was calculated for the lowest velocity case, $Re_D = 40$ K ($W_\infty = 4.19$ m/s), and within the vortex core, representing the worst-case scenario. The error is significantly lower in the freestream and higher-velocity cases.

III. WAKE STATES: REGIME AND TRANSITION

A. Reynolds number effects on drag transition

To investigate the effect of Reynolds number on the wake transition, drag measurements were obtained for both sharp- and rounded-edge afterbody models using the low-drag instrument. Figure 4 presents the drag coefficients, C_D , for the $\phi = 32^\circ$ and $\phi = 45^\circ$ models across a range of Reynolds numbers ($100 \text{ K} < Re_D < 200 \text{ K}$). This flow field was examined over a larger Reynolds number range ($15 \text{ K} < Re_D < 400 \text{ K}$), but the range shown in Fig. 4 was selected to highlight the observed transition.

For the sharp-edge models, which are characterized by a CS vortex state with a large recirculation region, the drag coefficient remains relatively constant throughout the tested Reynolds

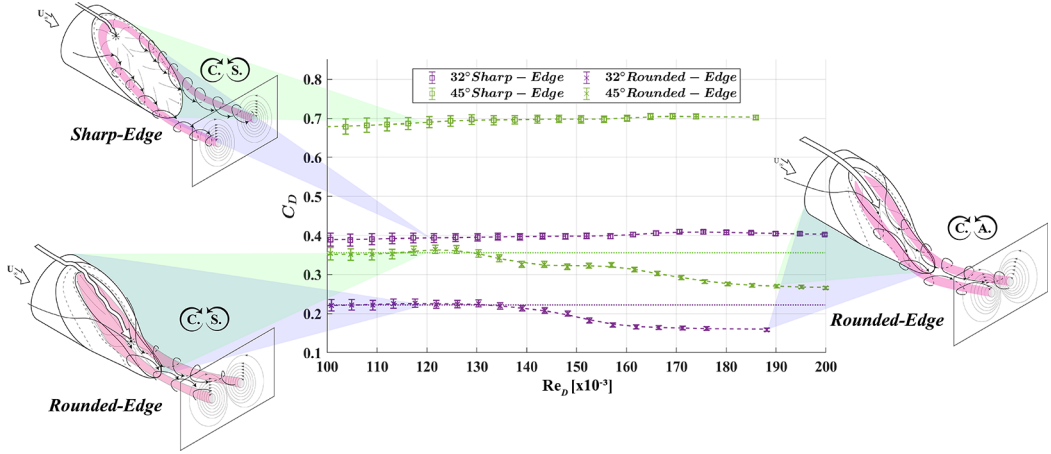


FIG. 4. Drag coefficient for several afterbody geometries over a range of Reynolds numbers. The horizontal dotted lines indicate the high drag measurements observed for the rounded-edge models. These lines are used to visually compare the drag measurements between the CS and CA vortex states.

number range. No significant drag transition is observed: the $\phi = 32^\circ$ sharp-edge model maintains $C_D \approx 0.40$, while the $\phi = 45^\circ$ sharp-edge model maintains $C_D \approx 0.70$. Prior studies have identified the drag transition for the 45° sharp-edge model to be at $Re_D \approx 32$ K, where the flow abruptly transitions from a low-drag fully separated wake state to a high-drag CS vortex state [7,13]. While intriguing, this transition is not the focus of this study and has not been included in Fig. 4, as it has been well documented in literature [6,7,13]. The Reynolds number range shown here illustrates the wake dynamics of the rounded-edge models, which are the focus of this study.

For the rounded-edge models, a noticeable reduction in drag coefficient occurs between $Re_D \approx 130$ K and $Re_D \approx 180$ K, after which the drag settles at a value approximately $0.1C_D$ lower. This decrease in drag is similar to the transition observed for the sharp-edge model, where a sudden change in wake state leads to a drag increase as the flow shifts from a fully separated vortex state to a CS vortex state [7,13]. However, in the rounded-edge case, the transition is characterized by a drag reduction rather than an increase, and the change occurs gradually over a range of Reynolds numbers rather than abruptly. This suggests that both the nature and mechanism of the transition differ between sharp- and rounded-edge geometries. Additionally, the similar transition Reynolds numbers observed for both rounded-edge slant angles imply that the transition may be largely independent of slant angle, and instead governed by upstream flow properties—likely the state of the boundary layer before the afterbody leading edge. It should be noted that only two slant angles were examined in this study. While this study covers a significant range of slant angles, the independence of slant angle may not strictly hold at the extremum, especially at larger slant angles, where one starts approaching a cylinder geometry.

Comparing between edge conditions, a substantial reduction in drag is observed. The $\phi = 45^\circ$ rounded-edge model exhibits a drag reduction of approximately $\Delta C_D \approx 0.35$ relative to the sharp-edge model. This reduction is attributed to decreased suction on the slant surface, which is directly related to a weakened recirculation region and downstream vortices [9,20]. Previous work by Bulathsinghala *et al.* [3] on the sharp-edge model demonstrated that, because of the continuous horseshoe connection between vortices and the recirculation region, vortices with lower circulation result in reduced flow entrainment into the recirculation region. This, in turn, leads to a higher base pressure on the slant surface and consequently lower drag. A similar trend is evident for the $\phi = 32^\circ$ models, further confirming that edge rounding consistently reduces the drag coefficient by weakening the recirculation region and downstream vortices.

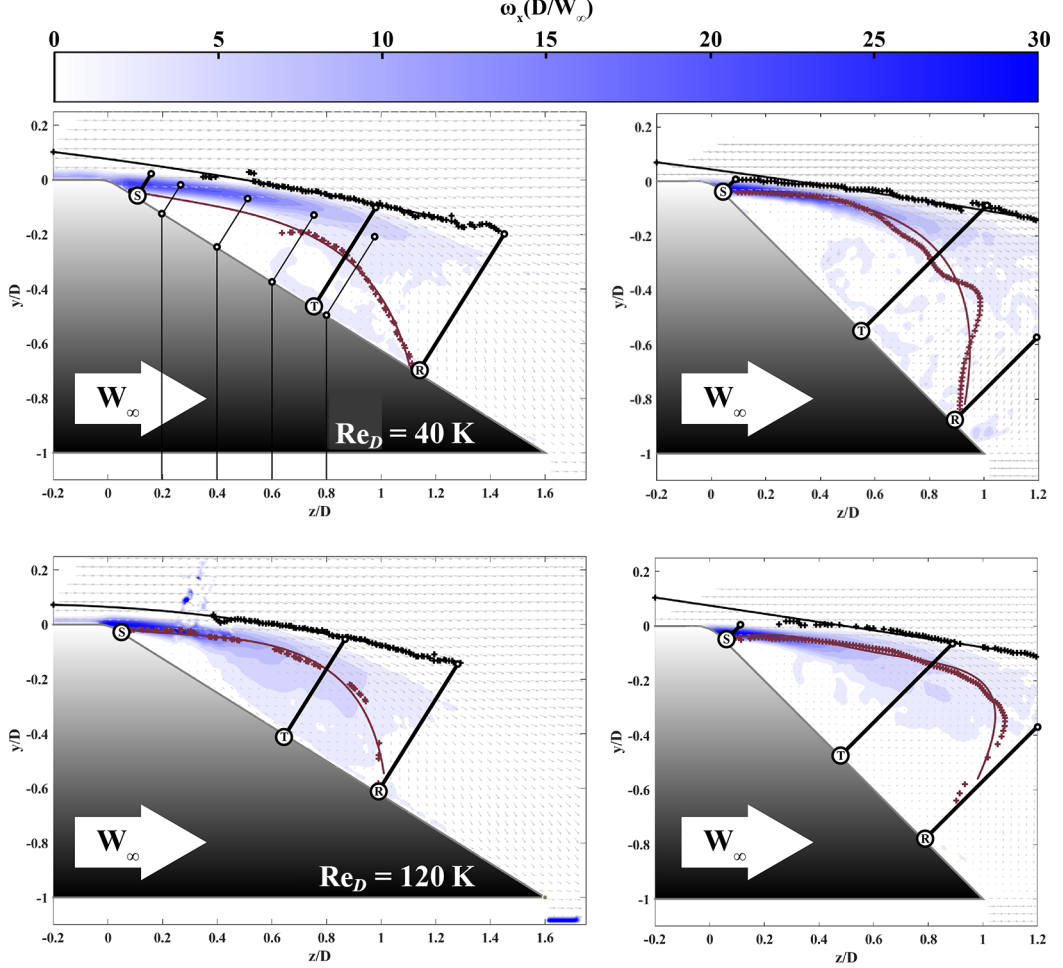


FIG. 5. Mean x -vorticity overlaid with velocity vectors at the model centerline for the rounded-edge configuration at $Re_D = 40$ K (top) and $Re_D = 120$ K (bottom). Left and right panels correspond to the $\phi = 32^\circ$ and $\phi = 45^\circ$ models, respectively. Also shown are the separation (encircled ‘S’), shear-layer transition (encircled ‘T’), and reattachment (encircled ‘R’) locations, along with the shear-layer edge (black ‘+’ symbols) and the mean dividing streamline (red ‘+’ symbols). Polynomial fits to the mean dividing streamline and shear-layer edge are shown by the red and black lines, respectively, representing the boundary of the recirculation region and the outer edge of the shear layer.

B. Effect of Reynolds number on centerline flow structure

To provide a detailed description of the centerline flow structure, planar PIV measurements were performed at targeted Reynolds numbers that describe the flow field prior to, during, and after the drag transition. Hence, $Re_D = 40$ K represents the flow prior to the drag transition, $Re_D = 120$ K and $Re_D = 150$ K represent the flow during the transition, and $Re_D = 190$ K represents the flow after the transition. Figures 5 and 6 show the corresponding mean spanwise or x -vorticity contours over the target Reynolds numbers of $Re_D = 40$ K, Fig. 5 (top), 120 K, Fig. 5 (bottom), 150 K, Fig. 6 (top), and 190 K, Fig. 6 (bottom) for the $\phi = 32^\circ$ (left) and $\phi = 45^\circ$ (right) rounded-edge models.

Beginning with the vorticity field at $Re_D = 40$ K, Fig. 5 (top), the flow exhibits properties synonymous with the centerline-separated (CS) vortex state. It is noted that this conclusion will be confirmed upon examining the produced, downstream, counterrotating vortices in Sec. V.

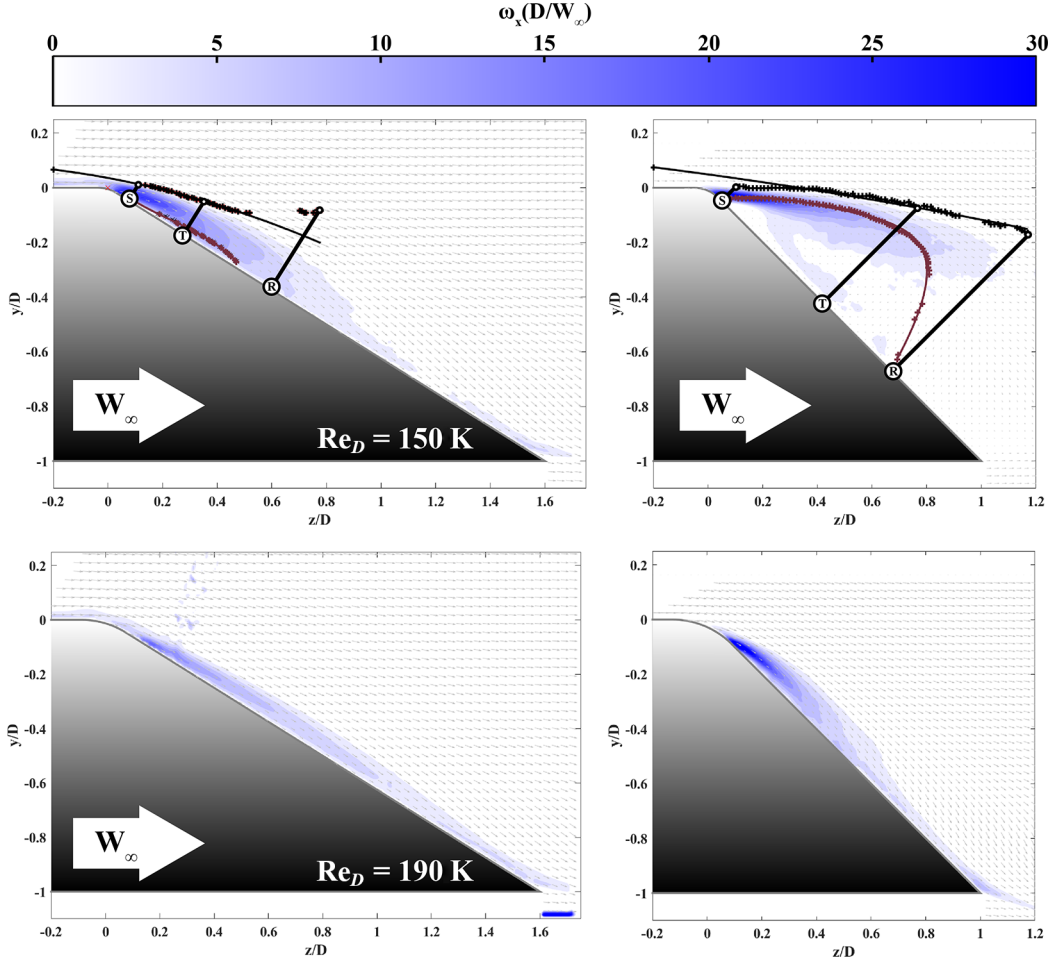


FIG. 6. Mean x-vorticity overlaid with velocity vectors at the model centerline for the rounded-edge configuration at $Re_D = 150$ K (top) and $Re_D = 190$ K (bottom). Left and right panels correspond to the $\phi = 32^\circ$ and $\phi = 45^\circ$ models, respectively. Also shown are the separation (encircled ‘S’), shear-layer transition (encircled ‘T’), and reattachment (encircled ‘R’) locations, along with the shear-layer edge (black ‘+’ symbols) and the mean dividing streamline (garnet ‘+’ symbols). Polynomial fits to the mean dividing streamline and shear-layer edge are shown by the garnet and black lines, respectively, representing the boundary of the recirculation region and the outer edge of the shear layer.

Concomitant with this flow state and supported by the illustration provided within Fig. 2, the incoming boundary layer separates on the leading edge radius, forming a free shear layer that is dominated by a strong region of vorticity. The shear layer is then seen to impinge, or reattach, on the model surface, closing in a large region of recirculation. It is known from prior studies that vortices form from shear layer rollup on the sides of the model. This recirculation region is connected to the vortices through a continuous rotating/vortical horseshoe-shaped connection [9]. A more detailed examination of the boundary layer is provided in Sec. IV A, while an in-depth overview of the shear layer is given in Sec. IV B.

Further analysis of this flow field highlights additional, relevant flow features. First, by using a local frame of reference that is parallel (s) and normal ($\perp s$) to the model surface, velocity profiles can be found along the slant. The separation location can therefore be defined as the first location

TABLE I. Summary of boundary layer and recirculation region properties with Reynolds number for $\phi = 32^\circ$ and $\phi = 45^\circ$ rounded-edge models. Unbolded rows correspond to Reynolds numbers that yield a CS vortex state, while bolded rows correspond to Reynolds numbers that yield a CA vortex state. z_S and z_R are the separation and reattachment locations respectively.

32° Rounded	Re_D	δ/D	θ/D	z_S/D	z_R/D	$\frac{z_R - z_S}{D}$
	40 K	0.036	0.0052	0.085	1.12	1.03
	120 K	0.022	0.0030	0.045	1.00	0.95
	150 K	0.021	0.0029	0.075	0.60	0.53
	190 K	0.027	0.0026	N/A	N/A	N/A
45° Rounded	Re_D	δ/D	θ/D	z_S/D	z_R/D	$\frac{z_R - z_S}{D}$
	40 K	0.031	0.0046	0.051	0.90	0.85
	120 K	0.022	0.0031	0.062	0.79	0.73
	150 K	0.024	0.0029	0.055	0.68	0.63
	190 K	0.024	0.0025	N/A	N/A	N/A

where the nearest resolvable s -velocity vector is zero/negative. This indicates reverse flow relative to the surface and is denoted by an encircled ‘S’ in Figs. 5 and 6, and the locations for both slant angles are tabulated in Table I as z_S/D . Additionally, the top edge of the shear layer is defined as the location of the maximum s -velocity vector in the same surface normal profile. The top edge of the shear layer is denoted by black ‘+’s in Figs. 5 and 6 and is fit with a second-order polynomial denoted by the black line. In a similar manner, the bottom edge of the shear layer is defined as the upper boundary of the recirculation region. The upper boundary of the recirculation region is identified by locating the mean dividing streamline (MDSL). This is determined by integrating the velocity profile normal to the surface and finding the location where the net mass flow rate is zero. These locations are defined by the garnet ‘+’s in Figs. 5 and 6 and are fit with a fourth-order polynomial denoted by the garnet line. Finally, the reattachment point is defined as the location of the last negative near-wall surface parallel velocity vector. The reattachment point is denoted by an encircled ‘R,’ and the location for both slant angles is tabulated in Table I as z_R/D .

Increasing the Reynolds number to $Re_D = 120$ K, Fig. 5 (bottom), and $Re_D = 150$ K, Fig. 6 (top), the observed wakes are within the CS vortex state with differences as compared to the $Re_D = 40$ K case. Each state still exhibits acceleration prior to separation, the formation of a free shear layer, reattachment, and formation of the recirculation region. However, the recirculation region reduces in size with increasing Reynolds number. This becomes clearer when examining the size of the recirculation region on the surface, i.e., $\frac{z_R - z_S}{D}$: the distance between the separation location, z_S/D , and the reattachment location, z_R/D . As shown in Table I, the value $\frac{z_R - z_S}{D}$ decreases with increasing Reynolds number for both slant angle configurations. This variation, although not large between the $Re_D = 40$ K and $Re_D = 120$ K cases, is significantly larger between $Re_D = 120$ K and $Re_D = 150$ K, which represents a mere ≈ 3 m/s difference. At $Re_D = 150$ K, the recirculation region length for the $\phi = 32^\circ$ model is nearly halved as compared to $Re_D = 120$ K. Referencing the drag measurements, Fig. 4, $Re_D = 120$ K corresponds to a Reynolds number just before the drag coefficient begins to decline, while $Re_D = 150$ K falls within the range where the drag is monotonically decreasing for both slant angles. Although the reduction in recirculation region size between $Re_D = 40$ K and $Re_D = 120$ K is not dramatic, the significant decrease observed between $Re_D = 120$ K and $Re_D = 150$ K suggests that the drag reduction is directly linked to the rapid reduction of the recirculation region.

Finally, Fig. 6 (bottom) displays the vorticity contours for $Re_D = 190$ K. At this Reynolds number, a striking transformation occurs: the incoming flow remains fully attached to the model surface, following its contours, and no separation or recirculation region is present for either slant angle. Although an increase in vorticity is observed near the model surface—particularly for the

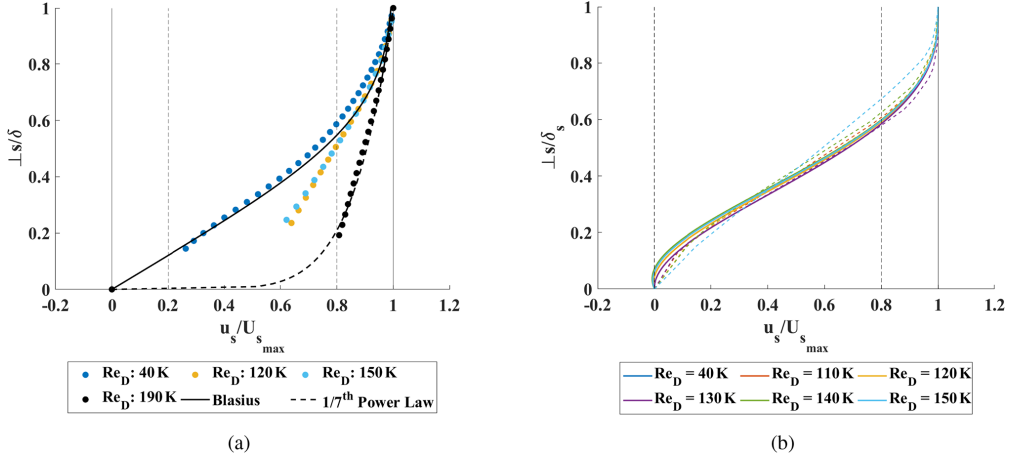


FIG. 7. Boundary layer profiles for the $\phi = 32^\circ$ rounded-edge model at various Reynolds numbers. $\perp s$ is the surface perpendicular coordinate, u_s is the surface parallel velocity, and $U_{s \max}$ is the maximum local surface parallel velocity. (a) Boundary layer profiles at $z/D = -0.2$, upstream of the rounded-edge, for varied Reynolds numbers. The solid black line represents the Blasius profile. The dashed black line represents the $1/7^{\text{th}}$ power law profile. (b) Boundary layer profiles (dashed) taken at respective separation locations for varied Reynolds numbers. Each profile is fit with a Pohlhausen profile (solid). See Figs. 5 and 6 for separation locations.

$\phi = 45^\circ$ model, which is suggestive of flow separation—analysis of near-wall velocity profiles confirms that there is no reverse flow present. The absence of reverse flow and the recirculation region marks a shift in wake topology, signifying a transition to the centerline-attached (CA) vortex state. The transition to the CA vortex state is further corroborated by the drag measurements in Fig. 4, where $Re_D = 190$ K corresponds to a Reynolds number just after the drag transition has completed and the drag coefficient has stabilized at a lower value. This is a clear indicator of a fundamentally different flow regime, with profound implications for downstream vortex structure and overall aerodynamic performance, i.e., less drag. The transition mechanisms and downstream impact will be discussed in the following sections.

The results presented in this section demonstrate a clear Reynolds number-driven transition from the centerline-separated (CS) vortex state to the centerline attached (CA) vortex state for the rounded-edge slanted afterbody. This transition is marked by a significant reduction in drag, which directly correlates with a rapid decrease in the length of the recirculation region at the model centerline. The following section will provide an in-depth analysis of the $\phi = 32^\circ$ model to demonstrate how this reduction in recirculation region length and drag is governed by the transition of the upstream boundary layer from laminar to turbulent.

IV. SEPARATION AND SEPARATION BUBBLE DYNAMICS

A. Boundary layer transition and influence on flow regimes

Shown in Fig. 7(a) are the boundary layer profiles for the $\phi = 32^\circ$ rounded-edge model for various Reynolds numbers at a location upstream of the radius ($z/D = -0.2$) and apparent flow acceleration. The profiles for the $\phi = 45^\circ$ model at the same location are nearly identical to those of the $\phi = 32^\circ$ model; for brevity, they are not shown. The conclusions regarding the corresponding boundary layer state are consistent across both slant angles. Boundary layer height and momentum thickness for both slant angle configurations and all Reynolds numbers are provided in Table I.

For the lowest Reynolds number case, $Re_D = 40$ K, the boundary layer profile is observed to agree with the Blasius profile, which is a solution to the laminar boundary layer equations. However,

as the Reynolds number increases, i.e., $Re_D = 120$ K and $Re_D = 150$ K, the boundary layer deviates from the laminar profile. At $Re_D = 190$ K, the profile aligns well with the $1/7$ th power law, which is representative of a turbulent boundary layer. The onset of a turbulent boundary layer at $Re_D = 190$ K aligns well with the expected transition Reynolds number for a flat plate, which is approximately $Re_x \approx 500$ K ($Re_D \approx 170$ K) [26].

The observed boundary layer transition coincides with the drag transition seen in Fig. 4, where the centerline flow field transitions from the CS vortex state to the CA vortex state seen in Figs. 5 and 6. These results suggest a strong connection between the state of the incoming boundary layer and the developed wake. Such an observation aligns with classical separation theory: separation occurs when the near-wall momentum cannot overcome the adverse pressure gradient. Turbulent boundary layers, with higher near-wall momentum, are more resistant to separation than laminar ones. As the boundary layer transitions to turbulence, the increased near-wall momentum allows the flow to remain attached to the surface. These results provide direct experimental evidence that a fully turbulent incoming boundary layer prevents the formation of a separation region at the model centerline for both the $\phi = 32^\circ$ and $\phi = 45^\circ$ configurations. Furthermore, these results corroborate the drag measurements presented in Sec. III A, indicating that the transition is largely independent of slant angle and controlled by upstream flow properties—at least over the range of angles examined in this study.

In addition to the boundary layer profiles, the velocity profiles are examined at the point of separation as shown in Fig. 7(b). In this figure, the raw values are shown by dashed lines and a Pohlhausen profile fit is shown by solid lines [26]. These profiles are nondimensionalized by the maximum local surface parallel velocity, $U_{s_{\max}}$, and the thickness at separation, δ_s . Coloring of the lines is consistent between Figs. 7(a) and 7(b) for ease of comparison.

As shown, the profiles at separation collapse. This indicates that the normalized shear at the point of separation remains nearly constant across all Reynolds numbers, including the transition region shown in Fig. 4. Previous studies have hypothesized that variations in shear at separation play a role in recirculation region size and corresponding drag [9]. However, as clearly shown in Fig. 7(b), the shear remains constant across all Reynolds numbers. This suggests that the shear at separation is not responsible for the observed changes in recirculation size/drag as has been previously hypothesized by Huss *et al.* [9].

In the following section, the separation bubble structure and dynamics will be examined, with comparisons to laminar separation bubbles drawn to provide further insight into the wake transition mechanisms.

B. Structure of the recirculation region

Horton [27], Gaster [28], and Howarth [29] outlined two-dimensional laminar separation bubble (LSB) theory for separated flow over an airfoil. While LSB theory provides a useful reference for understanding separated flows, its direct application to the present case is limited, particularly due to the three-dimensional nature of the flow in question. Nevertheless, certain features of the CS vortex state—such as the presence of a laminar boundary layer and a large recirculation region—allow for qualitative comparisons that help elucidate the structure of the recirculation region and inform discussion of transition mechanisms. Therefore, this section will primarily discuss these features from a two-dimensional perspective and Sec. V will discuss the impacts of these two-dimensional findings on the three-dimensional flow field, i.e., the downstream vortices. To guide this discussion, a schematic using LSB nomenclature applied to the CS vortex state centerline flow field is shown in Fig. 8.

In this figure, an incoming laminar boundary layer separates from the model surface at point ‘S,’ forming a laminar free shear layer. Once separated, the laminar shear layer contains comparatively weak viscous shear stresses. As a result, the shear layer cannot withstand significant adverse pressure gradients, leading to a nearly constant pressure along the model surface. However, once the shear layer transitions to turbulence at point ‘T,’ the average shear stress in the layer is increased,

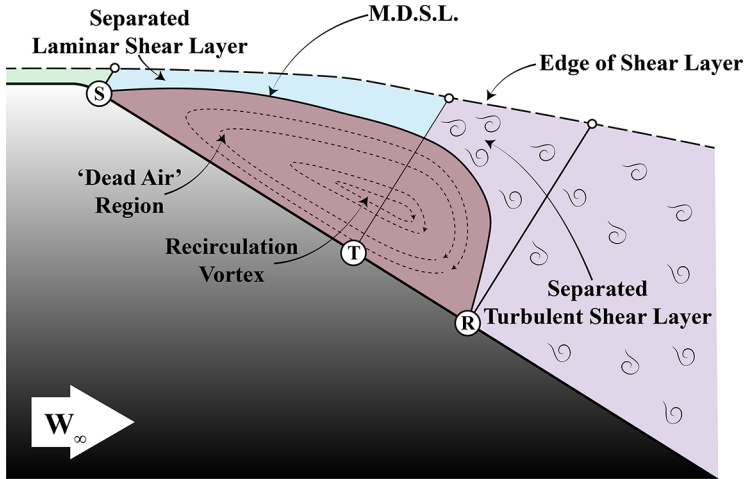


FIG. 8. Schematic of a two-dimensional LSB theory outlined by Horton [27] applied to the slanted afterbody.

and a pressure rise occurs until reattachment and the reformation of a turbulent boundary layer [29]. The pressure rise is generally linear between transition and reattachment and is accompanied by a rapid growth of the now-turbulent shear layer due to increased entrainment and mixing.

To clarify the physical interpretation, the pressure rise leading to reattachment can be understood as follows. Reattachment on the model occurs because, after the shear layer transitions to turbulence, enhanced mixing and entrainment cause the shear layer to thicken rapidly until it meets the surface. This growth leads the shear layer to impinge on the surface, resulting in reattachment. The associated pressure rise is therefore directly linked to this rapid increase in shear layer thickness and the onset of reattachment.

Comparing this theory to the centerline flow field of the slanted afterbody—specifically, the CS vortex state observed at low Reynolds numbers (see Fig. 5)—shows that the flow structure follows these principles. The incoming laminar boundary layer discussed in Sec. IV A separates at point ‘S’ and becomes a laminar-free shear layer. Additionally, rapid growth of the shear layer is observed prior to reattachment at point ‘R,’ which is suggestive of the transition to a turbulent shear layer. To further validate this hypothesis, the centerline pressure measurements for the $\phi = 32^\circ$ model are examined in Fig. 9.

The pressure distribution for the $Re_D = 40$ K case shows that, upstream of the separation location, a favorable pressure gradient is observed, which is associated with the observed flow acceleration. This is followed by an adverse pressure gradient around the model radius, leading to boundary layer separation. Once separated, i.e., within the recirculation region, the pressure is nearly constant for an extended length. This region of constant pressure corresponds to the presence of a laminar shear layer. Note that this negative constant pressure occurs over the large recirculation region and translates to a significant drag force. Following this region of constant suction, a steady pressure rise is seen, leading to the reattachment point. Again, this pressure rise is associated with the shear layer transition to a turbulent shear layer. The origin of this pressure rise was used to define the transition location, as shown by the circled ‘T’ in Fig. 9 and translated to Figs. 5 and 6.

To further validate the transition location, the standard deviation of the y -velocity component was calculated at each point in the shear layer. The standard deviation is a measure of the velocity fluctuations and is known to increase significantly and reach a maximum once the shear layer transitions to turbulence. Providing a low cutoff threshold of $\sigma_y/W_{\infty} = 0.15$, the transition location can be defined as the first point in the shear layer where the standard deviation exceeds this threshold. These locations were found to be $z/D = 0.74$, $z/D = 0.71$, and $z/D = 0.25$ for

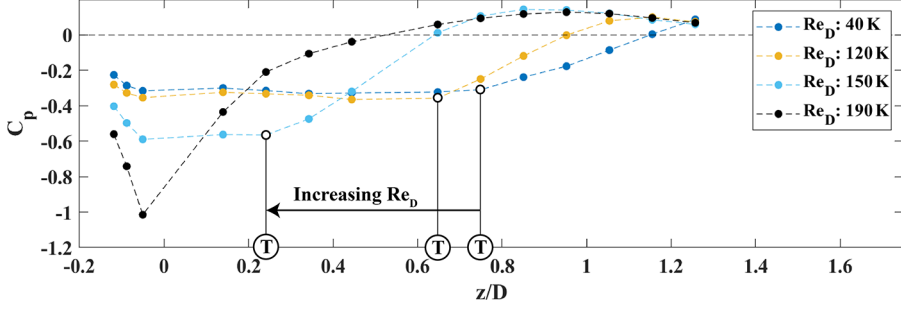


FIG. 9. Pressure Coefficient for the $\phi = 32^\circ$ rounded-edge model for Reynolds numbers $Re_D = 40$ K, 120 K, 150 K, and 190 K.

$Re_D = 40$ K, $Re_D = 120$ K, and $Re_D = 190$ K, respectively, and are in good agreement with the transition locations defined by the pressure rise, which are shown in Fig. 9. To remain consistent, the transition locations defined by the pressure rise are used for the remainder of this study.

These observed characteristics closely resemble those described in LSB theory by Howarth [29] and Gaster [28], suggesting that the centerline/symmetric plane of the recirculation region behaves similarly to a laminar separation bubble.

Considering now the effect of increasing Reynolds number on the centerline pressure measurements and the recirculation region, as shown in Sec. III B, the recirculation region size is reduced with increasing Reynolds number. This is confirmed by the pressure measurements, which show that the shear layer transition location moves upstream as Reynolds number increases—indicating earlier transition and earlier reattachment. Additionally, the gradient of the linear pressure rise is seen to increase with Reynolds number and is paired with an increase in suction spread over a smaller region.

After transition to an attached state, i.e., at $Re_D = 190$ K, the centerline pressure measurements display a steep favorable pressure gradient prior to the model radius. This favorable gradient directly transitions into a sharp adverse gradient, which is traditionally representative of flow separation. However, flow separation is not observed. Note, there is still a possibility that separation has occurred, but it is too small to be observed with the flow diagnostics utilized in this study. Additionally, although the suction region is large in magnitude, it covers a much smaller area compared to the other Reynolds numbers shown. This is a clear indication of the impact of the recirculation region on model drag—the absence of a recirculation region corresponds to a wake with minimal drag.

Another similarity between the two-dimensional LSB theory and the centerline flow field is the dependency of the separation bubble size on Reynolds number. Horton [27] notes the LSB size (regardless of whether it is short or long) contracts with increasing Reynolds number, an inverse relationship. This is because higher viscous forces at lower Reynolds numbers damp out disturbances in the shear layer, delaying transition to turbulence and allowing the recirculation region to spatially persist longer. As the Reynolds number increases, reduced viscous damping allows earlier transition, causing the recirculation region to contract.

As described in Sec. III B and Table I, while in the CS vortex state, the separation bubble size decreases with increasing Reynolds number, consistent with theory. This is beneficial to the discussion of the transition mechanism, as it has been discussed in Sec. IV A that the normalized shear at separation remains constant across Reynolds numbers and cannot be the cause of the observed changes in recirculation region size. Instead, the decrease in separation bubble size with increasing Reynolds number is attributed to the described reduced viscous damping at higher Reynolds numbers, which allows earlier transition and causes the recirculation region to contract.

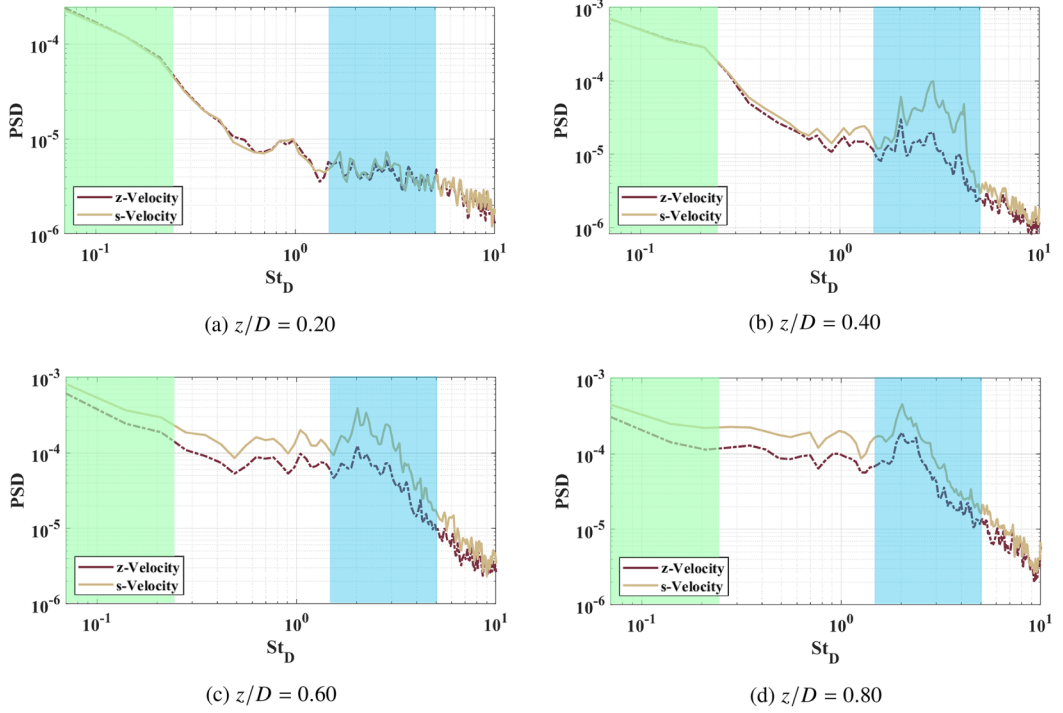


FIG. 10. Spectra within the shear layer at designated streamwise locations for the $\phi = 32^\circ$ configuration at $Re_D = 40$ K. Garnet and gold lines represent the z - and s -velocity components, respectively. Green and blue highlighted regions represent the low-frequency and high-frequency regions, respectively.

C. Recirculation region dynamics

To further understand the dynamics within the recirculation region, the unsteady behavior and spectral characteristics are examined. Figure 10 displays the power spectral density (shown in [1/Hz]) at a point taken midway between the MDSL and the shear layer at various streamwise locations for the $\phi = 32^\circ$ rounded-edge model at $Re_D = 40$ K. The z/D locations of these points are noted in the figure captions and described in Fig. 5. The spectra are calculated using Welch's overlapped segment averaging estimator with a Hanning window and 75% overlap. The spectra are shown for both the z - and s -velocity components (garnet and gold lines, respectively), where z is the streamwise direction and s is the surface parallel direction.

As seen in these figures, the spectra are dominated by two regions: a broadband low-frequency region, shown in green, and a high-frequency region, shown in blue. The low-frequency region is present in each spectrum along the length of the recirculation region. It is more prominent further upstream, for example, at $z/D = 0.20$, where the surrounding noise is damped. As the flow progresses downstream, a general increase in fluctuation magnitude dampens the impact of the low-frequency content, indicating the onset of turbulence. The high-frequency region can be defined at a peak Strouhal of $St_D \approx 2$ and is noted to grow as the flow propagates downstream.

Both of these frequency bands are consistent with the dynamics of LSBs. The low-frequency band is known to be associated with vertical oscillations of the shear layer, which are known as 'flapping,' and the high-frequency band is known to be associated with the short-wave instability of the separated shear layer [30]. This high-frequency instability is known to be responsible for the breakdown of the laminar shear layer and eventual transition to turbulence/correlated reattachment as described in Sec. IV B.

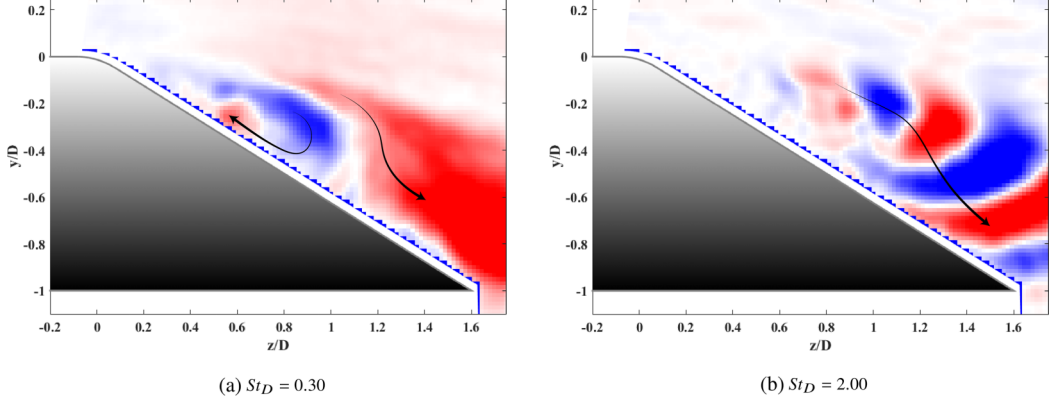


FIG. 11. Spectral proper orthogonal decomposition (SPOD) results for the $\phi = 32^\circ$ rounded-edge model targeting the lower-frequency band (a) and the higher-frequency band (b) for the CS vortex state at $Re_D = 40$ K.

A similar analysis was performed for the CA vortex state at $Re_D = 190$ K. As there is no recirculation region at this Reynolds number, the analysis targeted locations along the model surface. The spectra showed low-amplitude fluctuations with no discernible peaks.

To help visualize the structures associated with these frequencies, spectral proper orthogonal decomposition (SPOD) [31] is shown in Fig. 11. SPOD is performed on the z -velocity fluctuations ($w' = w - \bar{w}$) at the model centerline for the $\phi = 32^\circ$ rounded-edge model at $Re_D = 40$ K. Shown are the first modes at Strouhal numbers that target the lower-frequency band, $St_D = 0.30$ [Fig. 11(a)], and the higher frequency band, $St_D = 2.00$ [Fig. 11(b)]. 11% of the total energy is captured by the first mode at $St_D = 0.30$ and 5% of the total energy is captured by the first mode at $St_D = 2.00$.

Examining the lower-frequency band, Fig. 11(a), reveals large structures that propagate in two directions. The first propagates downstream, shedding off the body. The second propagates upstream in a rotational motion within the recirculation region. The divide between these two motions is near the reattachment point. These structures clearly indicate the low-frequency flapping of the shear layer.

Examining the higher-frequency band, Fig. 11(b), reveals smaller structures that appear confined to the shear layer and propagate downstream. These structures are indicative of the high-frequency short-wave instability of the shear layer, and the presence of these structures is known to be responsible for the transition of the shear layer to turbulence and eventual reattachment.

The combined evidence of the observed structures, their dynamics, and the associated spectral content confirms that the centerline flow field in the CS vortex state is characterized by a LSB that exhibits two frequency bands. A low-frequency band associated with the flapping of the shear layer and a high-frequency band associated with the short-wave instability of the separated shear layer. In contrast, the CA vortex state exhibits the absence of either frequency bands or a separated region. These findings clarify the physical mechanism underlying the CS-to-CA transition: it is driven by the short-wave instability that breaks down the laminar separated shear layer, forcing transition to turbulence and eventual reattachment. All of which is influenced by the upstream boundary layer state and transition, which are Reynolds number dependent.

While all of these are significant findings, it must be emphasized that the flow is inherently three-dimensional, and the centerline flow will strongly influence the downstream vortices. This is an especially important observation as, for the CS vortex state, the separation bubble is shown to dominate the centerline flow field and produce a largely turbulent flow field, characterized by shear layer flapping. It will be shown that the presence of this flow feature will not only increase the turbulence within the downstream vortices, affecting their structure, but also determine the frequency of their wandering. The influence of this centerline flow field—both its steady configuration

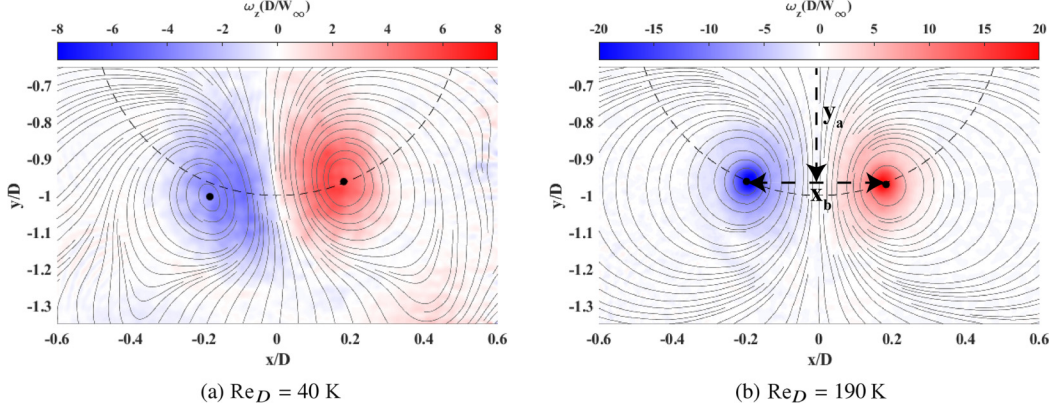


FIG. 12. Mean z -vorticity (ω_z) contours of the downstream vortices for the $\phi = 32^\circ$ rounded-edge model at $Re_D = 40$ K (a) and $Re_D = 190$ K (b) at a location $1D$ downstream of the trailing edge ($z/D = 2.6$). Black dots represent the vortex center as calculated by the theory set forth by Graftieaux *et al.* [32].

and unsteady spectral content—on the structure and dynamics of the downstream vortices will be addressed in the following section.

V. IMPACT OF CENTERLINE SEPARATION ON VORTEX STRUCTURE AND DYNAMICS

A. Mean vortex structure

Up to this point, the discussion has focused on the centerline flow state, specifically examining how the incoming boundary layer influences the properties of the recirculation region at the model centerline. In the Secs. IV B and IV C, this behavior was consistent with and reasonably well-explained through similarities with LSBs. However, this approach assumes two-dimensional flow wherein the present flow field is highly three-dimensional with strong longitudinal counterrotating vortices.

In reference to the three-dimensionality of the flow field, it is helpful to refer back to Fig. 2, which illustrates that the vortices are created by separation that occurs on the model edges, forming a shear layer, and rolling into the counterrotating vortices [6,7,9]. Within the CS vortex state, these vortices

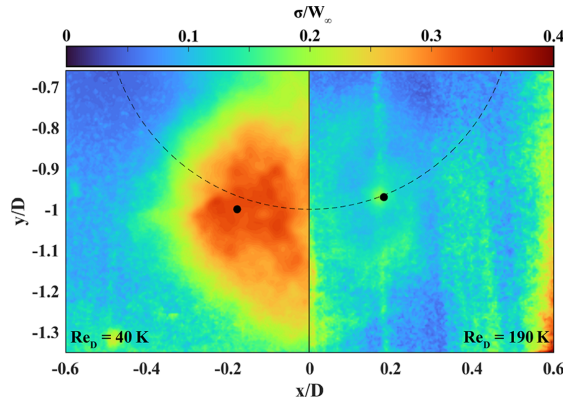


FIG. 13. Contours of the standard deviation of velocity magnitude (σ) for the downstream vortices of the $\phi = 32^\circ$ rounded-edge model at $Re_D = 40$ K (left) and $Re_D = 190$ K (right), measured $1D$ downstream of the trailing edge ($z/D = 2.6$). Black dots indicate the vortex centers, identified using the method of Graftieaux *et al.* [32].

TABLE II. Summary of vortex properties with Reynolds number for $\phi = 32^\circ$ and $\phi = 45^\circ$ rounded-edge models at a location $1D$ downstream of the trailing edge. Unbolded rows correspond to Reynolds numbers that yield a CS vortex state while bolded rows correspond to Reynolds numbers that yield a CA vortex state. x_a and y_a are defined as the horizontal spacing and vertical location of the vortex center, respectively, as shown in Fig. 12(b).

32° Rounded	Re_D	x_b/D	y_a/D	σ_{x_b}/D	σ_{y_a}/D	$\bar{\Gamma} [W_\infty D]^{-1}$
	40 K	0.335	-0.986	0.074	0.077	0.38
	120 K	0.337	-0.990	0.122	0.073	0.27
	150 K	0.374	-0.964	0.082	0.050	0.34
	190 K	0.379	-0.964	0.085	0.052	0.40
45° Rounded	Re_D	x_b/D	y_a/D	σ_{x_b}/D	σ_{y_a}/D	$\bar{\Gamma} [W_\infty D]^{-1}$
	40 K	0.263	-1.010	0.076	0.101	0.40
	120 K	0.237	-0.963	0.090	0.084	0.23
	150 K	0.287	-0.994	0.110	0.090	0.29
	190 K	0.408	-1.134	0.030	0.032	0.61

are known to connect through the centerline recirculation region, forming a horseshoe shape. Within the CA vortex state, they are disconnected due to attached flow at the centerline. Therefore, the structure and dynamics of the vortices are expected to be largely influenced by the centerline flow state, i.e., separated or attached.

To examine this influence on the downstream vortices, mean z -vorticity contours are displayed in Fig. 12 for the $\phi = 32^\circ$ rounded-edge model at $Re_D = 40$ K Fig. 12(a) and $Re_D = 190$ K Fig. 12(b). These spanwise slices are taken at a location $1D$ downstream of the trailing edge.

As can be clearly identified in these figures, both flow states contain a counterrotating vortex pair. This confirms that both flow states are vortex-dominated wakes. Pairing these figures with Figs. 5 and 6 confirms that the flow field observed at $Re_D = 40$ K corresponds to the CS vortex state and the flow field observed at $Re_D = 190$ K corresponds to the CA vortex state. Furthermore, this confirms the observed transition between $Re_D = 150$ K and $Re_D = 190$ K and extends the presence of these states beyond their previously observed existence at higher Reynolds numbers [9,10].

At $Re_D = 40$ K, the downstream vortices are seen to be spatially diffuse. In comparison, at $Re_D = 190$ K, the downstream vortices are seen to be well defined/structured with a tight core. Examination of the instantaneous vortex fields, not shown, reveals the vortices at $Re_D = 40$ K to be seemingly spatially incoherent at any given time step. The result of this spatial incoherence is the diffuse mean vorticity field. In contrast, the vortices at $Re_D = 190$ K are seen to be spatially coherent and well defined at any given time step. This is indicative of a more temporally and spatially stable vortex structure within the CA vortex state. The variance in spatial coherence is likely related to the centerline flow state, where the separated state introduces higher levels of turbulence into the flow field, generating a more diffuse vortex. This will be explored further within this section by examining the standard deviation of the velocity magnitude and by tracking the frequency of the vortex meandering and attempting to relate it to the previously discussed SPOD modes of the centerline recirculation region.

Circulation is calculated for each of the cases by integrating the vorticity field over an assumed circular integration window centered at the vortex core. The radius of the integration window is increased until the circulation measurements converge within 3%. The circulation measurements for both the $\phi = 32^\circ$ and $\phi = 45^\circ$ configurations for target Reynolds numbers are tabulated in Table II.

Despite the diffuse vortex observed at $Re_D = 40$ K, the circulation is seen to be comparable to the circulation at $Re_D = 190$ K for the $\phi = 32^\circ$ configuration. The same values for the $\phi = 45^\circ$ configuration as shown in Table II show a steep increase between the $Re_D = 40$ K and $Re_D = 190$ K cases. This indicates that, although the slant angle does not significantly affect the transition

location, its influence is not negligible (particularly at steeper angles). Interestingly enough, near transition, the circulation for both slant angles is observed to vary significantly, with a reduction at $Re_D = 120$ K before climbing to the circulation value at $Re_D = 190$ K. This variation is likely related to the reduction in the recirculation region.

The unsteadiness of the vortices can also be examined through the standard deviation of the instantaneous velocity fields, shown in Fig. 13. At $Re_D = 40$ K, the standard deviation of the velocity field is seen to be large, indicating a large amount of unsteadiness in the vortices spread over a large area. In contrast, at $Re_D = 190$ K, the standard deviation of the velocity field is seen to be small, indicating a small amount of unsteadiness in the vortices and a more coherent structure.

The variations between the vortices can be concluded to be a direct result of the centerline flow state. It is apparent that the presence of the centerline recirculation region/separation bubble introduces a large amount of unsteadiness into the flow field, specifically impacting the downstream vortices. With the absence of the centerline recirculation region, i.e., at $Re_D = 190$ K, the standard deviation highlights the vortex core. This suggests that, in this state, vortex meandering is the primary source of unsteadiness. To determine the specific mechanisms that contribute to these phenomena, a more in-depth analysis is provided in the following section.

B. Vortex dynamics

To gain insight into the dynamics of the vortex movement, the locations of all 10 000 instantaneous time steps over the primary Reynolds number conditions for both the $\phi = 32^\circ$ and $\phi = 45^\circ$ configurations were calculated. Due to the diffuse nature of the CS vortex case, the vortex tracking algorithm developed by Graftieaux *et al.* [32] was used due to its ability to locate vortex cores in largely asymmetric vortices and with subpixel accuracy. Additionally, a subwindowing method was used to limit the impact of outlier vortex locations that may be identified by the algorithm, particularly due to the diffuse nature of the CS vortex. This method searched a radius of $0.05 D$ from the previous vortex core location for the subsequent core location. Because the data were recorded at a high frequency (5 kHz) and the vortex core wandering is dominated by low-frequency motions [15,24], excursions of the vortex core locations beyond this search radius are not expected. The vortex core locations were post-processed with a median filter in both the x and y directions to further remove extraneous locations. Figure 14 shows the results for the $\phi = 32^\circ$ configuration. In these figures, the garnet and gold colors represent the left and right vortices, respectively. Additionally, the solid black line describes the first and second standard deviations calculated radially from the mean location. The $\phi = 45^\circ$ case is not shown for brevity and due to qualitatively similar results to the $\phi = 32^\circ$ case. However, the mean location and standard deviations in the x and y directions of the vortex core movements are tabulated in Table II for comparison. The general motion of the vortices will be described first before highlighting wandering frequencies and modes.

Examining the vortex locations over time reveals a clear dependency on Reynolds number. In the low Reynolds number ($Re_D = 40$ K), CS vortex state case, the vortex cores do not remain localized, but instead are scattered significantly both in the spanwise and vertical directions, indicating a high degree of unsteadiness. The core locations even cross the centerplane, further highlighting the extent of their wandering and the absence of a stable mean position. This phenomenon is likely tied to the presence of the large recirculation region at this condition. The recirculation region possesses a significant amount of turbulence which, due to its horseshoe-shaped connection to the vortices, propagates through the downstream vortices.

As the Reynolds number is increased into the transitional region, the vortices begin to stabilize and move toward the bottom radius of the model. Again, tied to the presence of the recirculation region, the vortices are observed to stabilize as the recirculation region decreases. However, the cores can still be described as scattered with a high degree of unsteadiness.

Once the model transitions to the CA vortex state ($Re_D = 190$ K), the vortex core dynamics change drastically. At this higher Reynolds number, the scattered locations nearly converge onto a

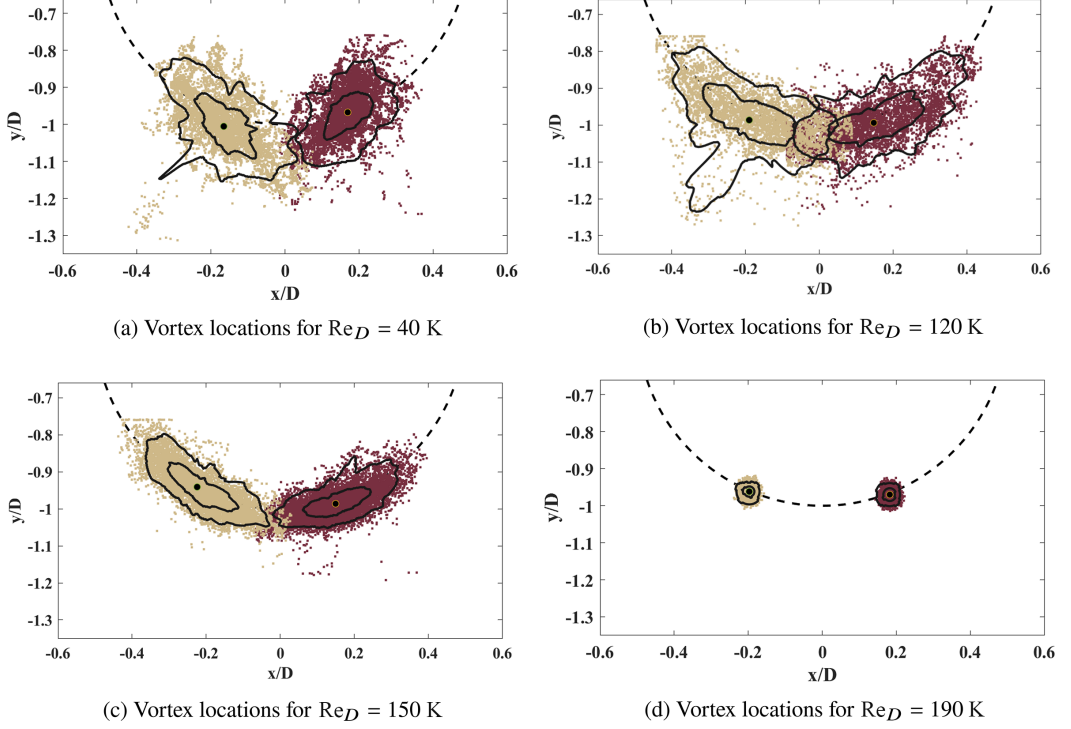


FIG. 14. Vortex core locations for the $\phi = 32^\circ$ rounded-edge model. Garnet and gold dots represent the core locations of the right and left vortices, respectively. The mean locations are shown by black dots. The black lines represent the first and second standard deviations from the mean.

single point, and the standard deviation is drastically reduced. It is clearly evident that the dynamics determining vortex locations are Reynolds number/centerline state dependent.

To determine the mechanisms that help determine the vortex wandering frequency, the power spectral densities (shown in [1/Hz]) of the vortex locations in both the x and y are shown in Fig. 15 for the $\phi = 32^\circ$ configuration at corresponding Reynolds numbers. These spectra are calculated using Welch’s overlapped segment averaging estimator with a Hanning window and 75% overlap.

For all cases within the CS vortex state [Figs. 15(a)–15(c)], the spectra are dominated by low-frequency unsteadiness with a broadband peak at a Strouhal number of $St_D \approx 0.15$. All higher frequencies display no clear peaks, indicating that the low-frequency oscillations are the primary source of unsteadiness in the CS vortex state. Note first that this is for both directions, x and y . Additionally, this low-frequency Strouhal number is consistent with previous computational and experimental findings on the rounded-edge $\phi = 32^\circ$ model at compressible speeds [20,24]. As the Reynolds number is increased, the low-frequency peak is seen to slightly shift to higher frequencies, indicating a slight Reynolds number or transition dependency.

Comparing this low-frequency unsteadiness with the centerline shear layer spectra in Fig. 10 shows that it aligns with the low-frequency band present in the shear layer dynamics. This correspondence demonstrates that the unsteadiness in the CS vortex state originates from large-scale, low-frequency oscillations of the shear layer—i.e., flapping. Evidently, the centerline separation and its respective low-frequency ‘flapping’ govern the structure, strength, and unsteady dynamics of the downstream vortices. The dominance and coherence of this mode across all operating conditions establish it as the principal dynamical mechanism governing the CS vortex state.

In the CA vortex state at $Re_D = 190$ K, the spectra are dominated by a high-frequency band whose Strouhal number is directionally dependent: $St_D \approx 0.7$ in the x direction and $St_D \approx 2$ in

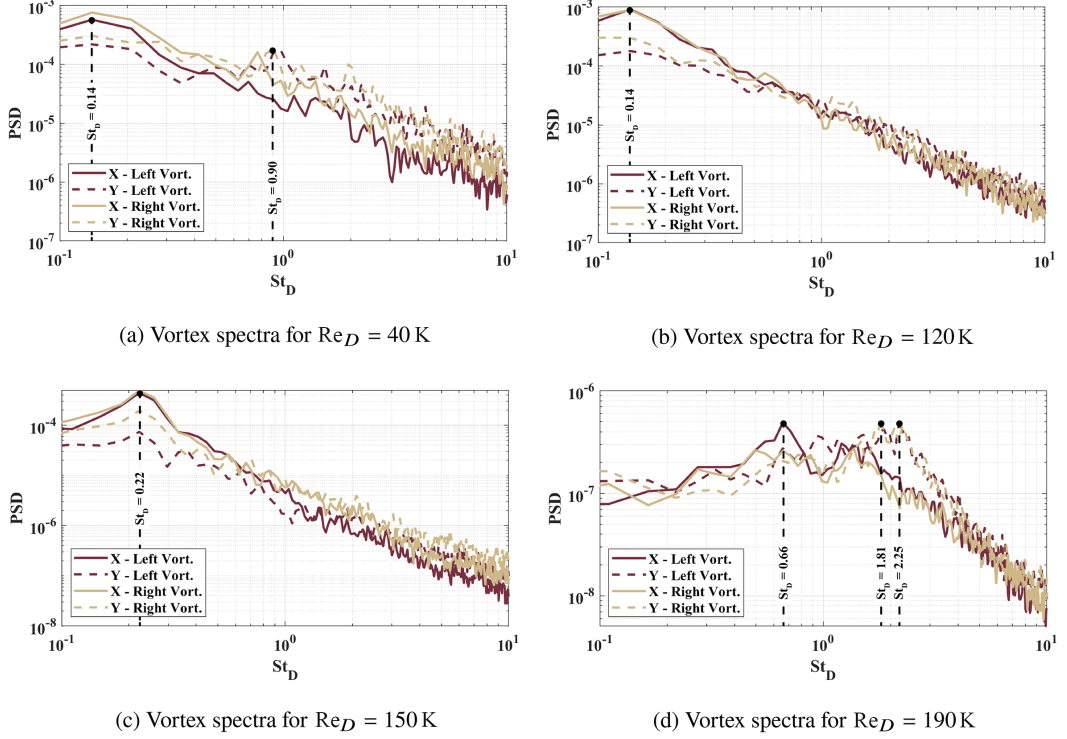


FIG. 15. Spectral analysis of the downstream vortex core wandering for the $\phi = 32^\circ$ rounded-edge model at varied Reynolds numbers. The garnet and gold lines represent left vortex and right vortices respectively. Solid and dashed lines represent the spanwise and vertical movement.

the y direction. The low-frequency band seen in the CS vortex state that is characteristic of LSB flapping is absent. This is consistent with the complete absence of the bubble at this Reynolds number. Notably, the y direction peak aligns with the short-wavelength instability of the separated shear layer observed in the centerline spectra of the low-Reynolds-number case. This suggests that, although the bubble flapping mode is absent, shear-layer-associated frequencies may still be present and may determine the vortex core wandering frequency. Overall, the evidence establishes that the vortex dynamics within the CS vortex state are defined by the centerline recirculation region (separation bubble), while the CA vortex state is controlled by a fundamentally different dynamical mechanism.

VI. CONCLUSIONS

This study has established the Reynolds number dependence of the rounded-edge slanted afterbody wake and revealed a previously undocumented transition from a centerline-separated (CS) vortex state to a centerline-attached (CA) vortex state between $Re_D \approx 130$ K and $Re_D \approx 180$ K. This transition was accompanied by a pronounced drag reduction, directly linked to the rapid reduction of the centerline recirculation region and the transition of the upstream boundary layer from laminar to turbulent. The reduction in recirculation length was attributed to diminished viscous damping at higher Reynolds numbers, enabling earlier shear layer transition.

The results show that the CS vortex state shares characteristics with LSBs, possessing two distinct spectral signatures: a low-frequency mode associated with shear layer flapping and a high-frequency mode arising from a short-wave shear layer instability. The latter drives the breakdown of the

laminar shear layer, forcing transition and reattachment. In contrast, the CA state exhibits neither frequency signature and lacks a separated region, indicating a fundamentally different underlying dynamical mechanism.

Additionally, the large-scale, coherent flapping of the separated shear layer was shown to govern the structure, strength, and dynamics of the downstream vortices. The persistence and dominance of this mode across all observed conditions established it as the principal driver of the CS state, generating highly unsteady and spatially diffuse vortical structures as compared to the largely steady and coherent structures observed in the CA state. These results provide new physical insight into the interplay between upstream boundary-layer transition, separated shear layer dynamics, and wake topology—offering a unified explanation for the CS-to-CA transition in bluff body wakes.

Overall, the centerline recirculation region is demonstrated to be the dominant mechanism governing the structure and dynamics of the CS wake state, while the CA vortex state is controlled by a fundamentally different mechanism. This work constitutes the first experimental evidence linking LSB dynamics, short-wave instability, and wake-state transitions in this canonical geometry.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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