The aerodynamic response to sideslip is crucial for an aircraft’s lateral stability, especially for configurations incorporating vortex flow, on which sideslip causes asymmetric vortex behavior and brings extra complexity. In this work, vortex flow over a close-coupled canard configuration under sideslip is simulated using delayed detached-eddy simulation, with the angle of attack varying up to the poststall regime. Sideslip-induced distinctions in both vortex dynamics and canard/wing-vortex interaction are analyzed to explain the nonlinear response of the configuration. The results reveal that the effect of sideslip differs significantly upon different angle-of-attack regimes. At a medium angle of attack, the spanwise extension of the low-pressure area due to windward vortex core expansion results in superior windward lift against the leeward side, but the relatively low pressure retained due to delay of the leeward vortex breakdown is the main motivation that leeward lift surpasses windward at a high angle of attack. The canard vortex trajectory deflected under sideslip induces asymmetric vortex interaction, enhancing the leeward side, which not only leads to an unusual rolling moment toward the higher lift side at a medium angle of attack but also causes an abrupt loss of lateral stability at the poststall angle of attack. A featured demarcation line exists on both the canard and the wing to separate the lift imbalance area, which is found useful in interpreting the nonlinear behavior.

### Nomenclature

- $C_L$, $C_D$, $C_N$ = lift, drag, and normal force coefficients
- $C_m$, $C_l$ = pitching- and rolling-moment coefficients (positive for nose up and toward starboard wing)
- $C_p$ = pressure coefficient
- $c$ = mean aerodynamic chord of the wing, m
- $D_{sub}$ = diameter of vortex subcore, mm
- $S$ = reference area, $m^2$
- $St$ = Strouhal number
- $U_x$, $U_y$ = axial and swirl velocities, m/s
- $U_{lmax}$ = maximum swirl velocity, m/s
- $U_w$ = vertical wash flow velocity, m/s
- $U_∞$ = freestream velocity, m/s
- $α$ = angle of attack
- $β$ = angle of sideslip
- $ΔC_p$ = difference of $C_p$ between windward and leeward sides; $C_{p_{wL}} - C_{p_{lL}}$

### Subscripts

- LWD = leeward side of sideslip
- WWD = windward side of sideslip

### I. Introduction

The close-coupled canard configuration has proven to be effective in delaying stall and increasing maximum lift at a high angle of attack (AOA) [1], the flow over which is of high complexity due to flow separation, vortex interaction, and breakdown of the vortex system. Despite its successful engineering application to several advanced fighters, the complicated flow mechanism of the vortex system still remains worthy of thorough research. What is ascertained up to now is that the aerodynamic advantages are achieved via favorable interaction between canard and wing vortices. Investigations by Tu [2], Tuncer and Platzer [3], and Howard and O’Leary [4] showed that vortex breakdown on the wing is effectively delayed by a close-coupled canard from medium to high A0As. The mechanism of breakdown delay is largely due to the downwash created by the canard vortex in the inner part of the wing, which reduces the local effective AOA, thus suppressing flow separation and delaying the formation of the wing’s leading-edge vortex [5]. The resultant improvement of the pressure field on the wing [6] yields lift enhancement. Ponton et al. [7] also found that the effect of the canard on lift enhancement continued to be significant, even when the configuration entered the poststall regime, which was also credited to the downwash generated by the canard.

Nevertheless, the majority of the previous research was conducted under symmetrical flow conditions, which scarcely exist in real flight, especially for agile fighters performing aggressive maneuvers that the close-coupled canard configuration is supposed to excel at. In fact, asymmetric flow caused by yaw or roll may have a great impact on the configuration’s aerodynamic performance, particularly for those incorporating vortex flow [8]; and the response to flow asymmetry is crucial for lateral stability and controllability. At a high AOA, in the lateral direction, unfavorable uncommanded nonlinear behavior occurs, among which the wing-rock phenomenon is the most common. Studies [9] on wing rock indicated that the oscillating motion was driven by vortex asymmetry near the wing-level condition. Ericsson [10] pointed out that the effective angle of sideslip under rolling affected the motion most and the period of oscillation was related to lateral static stability [11]. When a delta wing starts rolling, a switch between the critical states of the rolling moment exists, and Jenkins [12] found that there was a certain correlation between the roll critical states and the sideslip critical states. Therefore, in order to identify lateral nonlinearities and study the asymmetric vortical flowfield, many investigations were undertaken under configurations encountering sideslip, mostly upon delta or double delta (strake) wings.

Experiments conducted by Verhaagen and Jobe [13] and Verhaagen [14] tested a 65 deg delta wing at sideslip and a 30 deg AOA, which demonstrated the vortex breakdown difference with the windward breakdown promoted but leeward delayed. Acquired force and pressure data revealed that, although windward suction was diminished, the overall rolling moment was negative toward the leeward side, which was statically stable. But, rolling-moment curves versus sideslip in [11] or by Johnson et al. [15] showed that lateral
stability of the delta wings varied with the AOA and, at some critical AOA, instability occurred with the curve slope changing sign. It can be seen that vortex asymmetric breakdown brings complexity to the flowfield, but it is still easier to understand compared to configurations with not only one pair of leading-edge vortices. Under sideslip, double delta wings exhibit a vortex trajectory difference on both strake and wing vortices [16], and the leeward side witnesses enhanced coiling and merging of the vortices [17], inducing nonlinear forces together with vortex asymmetric breakdown. Due to the limitations of experiments in describing such a complex flowfield, numerical simulations [18,19] were also applied to unfold flow topology, the mean, and the instantaneous flowfield. So far, Reynolds-averaged Navier–Stokes (RANS) and detached-eddy simulation (DES) were commonly used to simulate the flow of the leading-edge vortex. Although RANS costs less in simulating the mean flowfield, DES works better in capturing the unsteady characteristics of vortices on various scales [20,21]. Jeans et al. [19] used delayed DES (DDES), which is a modified version of DES, to simulate a strake wing configuration at sideslip. Critical flow features were well displayed at a level of detail, and the investigation confirmed that the nonlinear aerodynamic behavior was primarily due to abrupt asymmetric vortex breakdown over the windward side, which was induced by a significant increase in total pressure depression and an adverse pressure gradient that the windward vortex experienced. However, as for the close-coupled canard configuration at sideslip, research was more rare and less profound. A previous study by Bandyopadhyay [22] incorporated a numerical method based on a vortex lattice model to predict sideslip-caused forces, but the method itself limited the precision at a high AOA, and the characteristics of the vortices were not shown in detail. Hebbel et al. [23] observed a wing-vortex breakdown difference on an X-31-like model at sideslip by flow visualization in a water tunnel; yet, the vortex interaction was not focused upon, and the canard’s favorable effect was not embodied. Other investigations, even including self-induced rolling of a canard configuration [24], were not comprehensive enough when seen from both the force measurement and the flowfield study, reflecting the necessity of understanding the changes in the flow mechanism under an asymmetric flow condition that triggered nonlinear behavior for this configuration.

In this work, a DDES based on a Spalart–Allmaras (S-A) turbulence model is adopted to simulate flow over a non-coplanar close-coupled canard configuration at various AOAAs under 0 to 10 deg sideslip. The objective is to investigate how sideslip influences the vortex system and interaction, as well as the motivation of lateral stability variation at different AOAAs. The results will paint a more detailed picture of the aerodynamic characteristics and flow physics of the close-coupled canard configuration.

II. Numerical Method, Model, and Validation

A. Flow Solver

All simulations in this study are solved using Ansys Fluent 14.0 by the finite volume method. The DDES grounded on the S-A model is selected to solve the unsteady incompressible flow. DES is a hybrid of RANS and the large-eddy simulation (LES), which solves the RANS equation near the wall and applies the LES in regions outside the boundary layer with massive separation [25]. The one-equation S-A model is used as the basic RANS formulation, which introduces a model-dependent variable $\tilde{\nu}$ related to the turbulent viscosity. The destruction term in the S-A model is proportional to $\tilde{\nu}^2$. To realize the DES, the wall distance $d$ in the S-A model is replaced by $\tilde{d} = \min(d, C_{DES}\Delta)$, where $C_{DES}$ is a constant calibrated using the decay of isotropic turbulence and $\Delta$ is the maximum geometric size of the local grid. Flow near the wall indicates $\tilde{d} < C_{DES}\Delta$, thus $\tilde{d} = d$, and the DES model converts to the S-A model. As the distance to the wall of the local grid increases and exceeds $C_{DES}\Delta$, $d$ equals $C_{DES}\Delta$, and the decay of the turbulent viscosity is determined by local grid size. The production term and the destruction term of the turbulent viscosity will finally reach an equilibrium state as $d$ further increases, and then the DES model acts as in a Smagorinsky LES mode. Based on DES, the DDES introduces a delay formula [26], which rebuilds $\tilde{d}$ to relate it not only with grid size but also with turbulent viscosity. Thus, the possibility to have numerical separation induced by improper grid size in DES is minimized in DDES, and DDES has proven satisfactory in simulating flow over the canard configuration [27].

To deal with pressure–velocity coupling, the SIMPLEC algorithm is applied and the diffusion terms are discretized by the central-differencing scheme, with the convection terms discretized by the second-order upwind scheme. For unsteady terms, the second-order implicit scheme is used.

B. Model Geometry

The close-coupled canard configuration in this study is picked from the model series of low-speed wind-tunnel experiments previously tested by Ma et al. [28] and Liu et al. [29,30]. A non-coplanar configuration constituted of a 60 deg swept canard and a 40 deg swept delta wing is chosen, named W40C60. The sketch and dimensions of the W40C60 computational model are shown in Fig. 1. The canard’s upper surface is shifted above the wing’s upper surface by 13 mm, and the apex of the wing is located right on the projected trailing edge of the canard. Several simplifications are made on the computational model from the one in the wind tunnel, including the elimination of a canard supporting structure and the shortened rear sting to the end of the wing. The reference area in this work is set to be the sum of both the canard and the wing platform area.

C. Zero-Sideslip Experiment

The wind-tunnel experiment including the force and pressure measurement has been conducted with the W40C60 model under zero sideslip in the D4 wind tunnel at the Beijing University of Aeronautics and Astronautics. The D4 wind tunnel has a 1.5 $\times$ 1.5 m square-shaped test section with a 2.5 m length. The turbulence intensity at the test section was less than 0.08%. For more information about the wind tunnel, see [29,30]. The freestream velocity of this experiment is 20 m/s, and the Reynolds number based on the mean aerodynamic chord of the wing is 2.0 $\times$ 10$^6$. The measurement of the forces with a strain-gauge balance have a 200 Hz sample frequency, and the time average is made of over 800 sample points. Surface pressure data are acquired by a 512-channel PSD9816 pressure scanner, with pressure holes arranged at $x_w/c_{rw} = 0.3, 0.4, 0.5, 0.6, 0.7,$ and 0.8 (port side shown in Fig. 1).

D. Mesh and Boundary Conditions

The computational domain is rectangular, as illustrated in Fig. 2, which also shows the boundary conditions for the half-model simulation. The half-model simulation is only adopted in the following grid independence study and zero-sideslip validation to reduce computation of calculation resources. The data under sideslip...
are all derived from a full-model simulation. The full-model mesh is mirrored by a half-model mesh with minor alterations in the boundary condition that the starboard flank boundary is changed from pressure outlet to velocity inlet, and the symmetry boundary condition on the plane of symmetry is eliminated. Y-block topology is applied to build constructed mesh for the delta-shaped canard and wing, and the height of first layer grid at the wall is set to let $y^+ \leq 1$.

The freestream velocity at the inlet is $20 \text{ m/s}$ with $0.08\%$ turbulence intensity, which coincides with the experiment and remains unchanged in both the half- or full-model simulation.

**E. Grid Independence Study**

Three sets of constructed meshes for the W40C60 model are generated in the half-model computational domain to verify the most proper grid resolution. The meshes (named grids A, B, and C) differ in both volume and surface distribution of nodes but keep the height of the first layer grid unchanged, and the quantities of volume cells are 3, 5, and 7.6 million, respectively. Surface element distribution is shown in Fig. 3a, and the volume element distribution of grid B is drawn in Fig. 3b. The time-step size throughout this work is fixed to $1 - e^{-4}$ s, which is derived from the Strouhal number of shear layer instabilities occurring over delta wings, $St = 10$ [31], taking one-tenth of its period. Table 1 shows the differences between the three sets of mesh on the calculated lift coefficient at 18 and 26 deg AOs. The time cost is gathered on a server machine with 16 2.6 GHz processors and 15.6 GB of RAM. Although the densest grid (grid C) provides minimum error, the heaviest consumption in time and computational resources is unaffordable. A tradeoff is made to set grid B as the standard of grid resolution and the nodal distribution for the following study, and a parallel run between two servers is established to deal with 10-million-grid full-model simulations at sideslip.

**F. Validation**

The aerodynamic coefficients simulated using grid B at AOAs up to 40 deg are displayed in Fig. 4, compared with experimental results. It can be seen that the configuration stalls at a 26 deg AOA, before which the computational and experimental results excellently coincided as the maximum relative error appeared less than 1.6%. In the poststall regime, the lift coefficient of the simulation drops below the experimental data, but the overall accuracy is acceptable. Contrast of the surface pressure distribution shown in Fig. 5 reveals that the simulation captures the prestall suction peak precisely, but at a 30 deg AOA, the computational result fails to rise up to the experimental value, causing the mismatch of lift. Taking precision into account, the following study involving sideslip limits the maximum AOA to 30 deg, which is already in the poststall regime.

**III. Results and Discussion**

**A. Effect of Sideslip on Aerodynamic Forces**

Simulations are performed at 10, 20, and 30 deg AOAs with angles of sideslip (AOSs) ranging from 0 to 10 deg at each incidence. The resultant aerodynamic coefficients of W40C60 are displayed in Fig. 6. Upon the increase of the AOS, the lift, drag, and pitching moment vary in a similar fashion. At 10 and 20 deg AOAs, the lift and drag more or less witness a decrease with the pitchup moment slightly diminishing as well, but at a 30 deg AOA, a minor AOS around 1 deg will first cause a dramatic increase in those three coefficients; after which, a much larger drop follows. The variation of the rolling moment (Fig. 6d) exhibits an obvious difference and critical features. At a 10 deg AOA, positive sideslip yields a negative rolling moment and the derivative always appears as $\partial C_{l}/\partial \beta < 0$, which represents a lateral stable condition. At a 20 deg AOA, the rolling moment fluctuates around zero and positive $\partial C_{l}/\partial \beta$ exists, indicating the
onset of lateral stability loss. Finally, an enormous positive rolling moment is generated at a 30 deg AOA, showing the aggravation of stability loss on the configuration; but beyond a 5 deg AOS, the configuration recovers to a stable condition, yet the positive rolling moment is still quite large.

To figure out the exact contribution of leeward and windward sides (relative to sideslip) to lift and rolling moments, the respective increment of the normal force coefficient due to sideslip on both sides is presented in Fig. 7a, and the increment of the absolute rolling-moment coefficient is shown in Fig. 7b. Seen from Fig. 7a, at 10 and 20 deg AOA, the normal force on the windward side appears larger than the leeward on both the canard and the wing, the margin of which is magnified with increasing sideslip. However, the situation at a 30 deg AOA is totally opposite. Especially on the wing, the leeward normal force overrides windward and the margin is considerably higher than that at lower AOA under the same sideslip. Similar behavior of the normal force is also observed on a canard within a 7 deg AOS but with a smaller margin. This exchange of the lift superior side from windward to leeward is the main reason of direction change in the rolling moment and will finally cause a strong positive rolling moment at a poststall AOA, shown in Fig. 6d.

Figure 7b directly demonstrates the rolling-moment difference caused by unequal normal force. A comparison with Fig. 7a shows that the variation of the absolute rolling moment generally follows the trend of normal force change at 10 and 30 deg AOA, but at a 20 deg AOA, obvious divergence turns up, particularly on the wing. At this incidence, normal force on the windward wing is larger but does not provide an overwhelming rolling moment against the leeward side. On the contrary, the whole configuration experiences a positive rolling moment toward the windward side, and this unusual rolling behavior is not specifically reported in previous studies. It can be judged that the fluctuation of the rolling moment upon increasing the AOS seen in Fig. 6d is exactly originated by this phenomenon, which will cause divergence in lateral stability at a 20 deg AOA.

It is clearly displayed that the effect of sideslip on the close-coupled canard configuration differs significantly upon different AOA regimes and the following flowfield study should particularly pay attention on these two questions raised from preceding descriptions, which are critical to the configuration’s lateral stability. First, what is the motivation of the exchange in the lift superior side? Second, what is the physical origin of the unusual rolling moment at a 20 deg AOA and the enormous positive rolling moment at a 30 deg AOA?

B. Flow Features

Major vortex structures are displayed in Fig. 8 for each AOA under 0 and 5 deg sideslips, using the Q vortex identification criterion [32]. Plotted in Fig. 8 are isosurfaces of instantaneous $Q = 2.5 \times 10^5 \text{s}^{-2}$ colored by streamwise velocity. Note that the bottom side of the graph is windward for situations at sideslip. Vortex structures at 10 and 20 deg AOA (Figs. 9a and 9b) are similar, and no vortex merging is shown, but vortex breakdown of both the wing vortex and canard trailing vortex appears fiercer at a 20 deg AOA. At a 30 deg AOA, as the wing vortex has already degenerated into fully separated flow, the configuration stalls (Fig. 9c). The effect of sideslip on the vortex structure is obviously seen in Figs. 8d and 8e, in that the trajectory of the canard trailing vortex is tilted toward the streamwise direction and the vortex breakdown over the windward wing at a 20 deg AOA seems to be aggravated. Another key feature is found in Fig. 8f, in that the leeward wing vortex, which is supposed to have disappeared at zero sideslip, still remains in a concentrating form with identifiable vortex structure, whereas separation dominates the windward wing as it is at zero sideslip. Further investigations into the flowfield will connect these critical flow features to the aerodynamic behavior.

C. Effect of Sideslip on Canard Vortex

1. Effect on Vortex Dynamics and Pressure Distribution

The axial velocity distribution along the canard vortex core at a 20 deg AOA is given in Fig. 9. Note that the black line with squares is extracted at zero sideslip and stays exactly the same in Figs. 9a and 9b. It can be inferred that non-sideslip breakdown occurs at approximately 0.35$c_{cr}$, since the axial velocity sees an abrupt depression. As the AOS increases, the location of the leeward axial velocity depression moves downstream but windward upstream, indicating the effect of sideslip that delays leeward vortex breakdown and promotes windward, which coincides with the results of [13, 14].

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**Table 1** Lift coefficient comparison between calculation and experiment for three mesh sets

<table>
<thead>
<tr>
<th>$\alpha$ (deg)</th>
<th>Experimental value</th>
<th>Grid A error (%)</th>
<th>Grid B error (%)</th>
<th>Grid C error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>0.86034</td>
<td>0.85461 (0.67%)</td>
<td>0.85617 (0.48%)</td>
<td>0.85592 (0.51%)</td>
</tr>
<tr>
<td>26</td>
<td>1.07875</td>
<td>1.05104 (2.57%)</td>
<td>1.06162 (1.59%)</td>
<td>1.06551 (1.23%)</td>
</tr>
<tr>
<td>Time cost per time step/s</td>
<td>—</td>
<td>—</td>
<td>80</td>
<td>110</td>
</tr>
</tbody>
</table>

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**Fig. 4** Calculated aerodynamic coefficients without sideslip along with experimental result (CFD denotes computational fluid dynamics and EXP denotes experiment).

**Fig. 5** Comparison of calculated pressure coefficient distribution against experimental result.
Additionally, the leeward axial velocity at the trailing edge is higher than both the windward side and zero sideslip.

The corresponding pressure coefficient distribution along the canard vortex core follows in Fig. 10. A severe adverse pressure gradient is exhibited near the vortex breakdown point, and it is important to notice here that sideslip affects not only breakdown point but also the strength of the vortex that is reflected on the pressure coefficient. For the leeward vortex, low pressure at the core before breakdown gradually recovers with increasing sideslip, but the windward vortex acts oppositely, which means that, regardless of breakdown difference, sideslip is actually weakening the leeward vortex but enhancing the windward vortex. However, it can also be inferred from the slope of the pressure coefficient curve that the magnitude of the adverse pressure gradient seems not to change upon sideslip. Thus, the windward vortex experiences a more dramatic pressure rise when breakdown occurs.
Figure 11 shows key characteristics of the canard vortex that will eventually influence aerodynamic forces, including the vortex position, the size of the subcore, and the swirl velocity. Here, the swirl velocity is extracted from perpendicular lines that go through both vortex cores, as illustrated in Fig. 11a, taking a 0.6c_{rc} plane for instance. The swirl velocity profile at the 0.6c_{rc} plane is displayed in Fig. 11b. The diameter of the vortex subcore is defined as the vertical distance between two summits of the profile and selects the velocity value at the lower summit as the maximum swirl velocity $U_{t, max}$.

Seen from Figs. 11c and 11d, at a 20 deg AOA and 5 deg sideslip, the height difference between the leeward and windward vortices is negligible over the canard, but the spanwise location of the windward vortex is apparently more inboard than leeward. The variation of the canard vortex size is shown in Fig. 11e, where $b$ is the local half-span. Due to promoted breakdown, the subcore of the windward vortex
continues to expand, so the size of the leeward vortex appears to be smaller aft of 0.2\(c_r\). Rapid expansion of the leeward vortex core due to vortex breakdown takes place around 0.7\(c_r\); yet, even after that, the leeward subcore is still smaller than the windward. The vortex parameters will directly affect surface suction by the maximum swirl velocity, shown in Fig. 11f, which is believed to involve both the vortex strength described in Fig. 10 and the breakdown difference. Before 0.2\(c_r\), seen from Fig. 10, pressure at the windward vortex core is much lower than windward, implying a stronger process of swirling. Therefore, in Fig. 11f at 0.2\(c_r\), the \(U_{t_{\text{max}}}\) of the windward side is higher. As the difference of the breakdown stands out, the leeward vortex core in turn possesses lower pressure within 0.2 to 0.7\(c_r\); hence, the leeward vortex has higher \(U_{t_{\text{max}}}\) from 0.3\(c_r\) to 0.7\(c_r\). The difference of \(U_{t_{\text{max}}}\) diminishes after 0.7\(c_r\), since breakdown occurs on both sides.

As a consequence of the vortex characteristics discussed previously, the surface pressure distribution on the canard has the following features. First, the magnitude of the suction peak is decided by \(U_{t_{\text{max}}}\). Seen from Fig. 11f, \(U_{t_{\text{max}}}\) at 0.3\(c_r\) on both sides approximately equals at a 5 deg AOS and, in Fig. 12a, the suction peaks on both sides also have close values of pressure coefficient. At 0.6\(c_r\), leeward \(U_{t_{\text{max}}}\) prevails, hence higher suction (Fig. 12b), and the difference on the suction value enlarges with an increasing AOS. Second, the spanwise position of the vortex shifts the location of the suction peak and the diameter of the subcore determines the width of the suction infected area. It can be found in Fig. 12 that, upon increasing sideslip, the windward suction moves inboard and grows wider, and the leeward suction acts in an opposite way.

The variation of the surface pressure distribution on the canard at a 30 deg AOA (Fig. 13) generally resembles that at a 20 deg AOA but does have some distinctions. The most eye catching is that, at 10 deg, the distribution is not consistent with that at a lower AOS anymore, which even looks like a calculation error. However, this phenomenon is due to the high AOS at a high incidence angle that has brought crossflow between the vortices at the canard apex, which is also responsible for windward canard lift overtaking the leeward side in Fig. 7a. As is shown in Fig. 14, the windward vortex extends across the symmetry plane and the development of each vortex is not independent. Further increasing the AOS will aggravate this tendency and bring about a saddle point on the surface flow topology [33,34], which is beyond the scope of this paper. What should be well noticed here is that, unlike the 20 deg AOA, the leeward suction peak is always higher than the zero-sideslip one, even when the AOS is small. The reason can also be found in Fig. 14 that, at a 30 deg AOA, vortex breakdown under zero sideslip occurs far upstream and sideslip’s effect of delaying the leeward breakdown is remarkable, thus inducing higher suction over most of the leeward surface.

2. Mechanism of the Exchange in Lift Superior Side

It should be noticed in advance here that the unequal lift between the leeward and windward sides is caused by asymmetric pressure distribution on both the lower and upper surfaces. Taking the 0.6\(c_r\) section, for instance, integration about \(C_p = 0\) is performed on each side’s upper and lower surfaces separately, and \(k_{LS}\) is defined in Fig. 15a to represent the contribution of the lower surface on total
unequal lift. It can be identified in Figs. 12 and 13 that the lower surface always encourages higher windward lift; thus, in Fig. 15b, \( k_{LS} \) drops below zero at a 30 deg AOA, since the total leeward lift is higher, exhibiting a negative effect. As sideslip increases, not only positive \( k_{LS} \) at a 20 deg AOA diminishes but also negative \( k_{LS} \) at a 30 deg AOA grows. Therefore, the lower surface does not play a decisive role in lift change, and the upper surface with a difference of vortex dynamics is the exact root of changing unequal lift.

To demonstrate the asymmetric pressure distribution on the key upper surface, subtraction of the pressure coefficient is undertaken between the windward and leeward sides, and the resultant \( \Delta C_P = C_{P_WW} - C_{P_LW} \) is displayed in contour on the windward side, as highlighted in Figs. 16 and 17. In the plots, the blue areas represent \( \Delta C_P < 0 \), which means the windward lift exceeds the leeward side; and the red areas indicate leeward lift superiority.

From Fig. 16, distinctive demarcation between the areas for windward and leeward lift superiorities can be clearly spotted. Putting the projected trajectory of the vortex core at sideslip on the plots finds that the demarcation line happens to coincide with the vortex trajectory, which also indicates that the demarcation line does not change upon varying the AOS. Inboard of the demarcation line, windward lift is obviously superior as the blue area dominates, but outboard of the demarcation line, the leeward lift seems to possess a greater sphere of influence. Increasing the AOS enhances both sides’ lift superiorities and enlarges the infected area but in different amounts. At a 20 deg AOA, shown in Fig. 16, the area of windward lift superiority appears far more extensive than the other side, and with a higher maximum absolute value of \( \Delta C_P \). Therefore, the canard windward lift at this moment is higher than the leeward side. Combining the analysis in the last section, inference can be made that the vast extension of windward lift superiority area is due to the expansion of the windward vortex subcore, which plays the most important role here to establish higher windward lift.

However, at a 30 deg AOA (Fig. 17), the situation is apparently different. Although the demarcation line is still near the zero-sideslip vortex trajectory (under the current AOA), only with a little spacing, the strength of both parties beside the demarcation line has changed. It can be seen that the area of leeward lift superiority flourishes compared to that at a 20 deg AOA, and \( \Delta C_P \) of this side is considerably larger. Despite increasing its infected area in the same
time, the windward lift superiority is relatively weakened. As a result, the canard leeward lift overrides the windward side and the exchange happens. It is not hard to find here that the sharp growth of the leeward lift superiority area, especially with rather low pressure retained, is the motivation of lift exchange.Derived from the analysis in the last section, at this moment, the delay of the leeward vortex breakdown turns out to be the key contributor.

D. Effect of Sideslip on Wing Vortex and Vortex Interaction

1. Influence on Prestall Vortex Interaction

The mechanism of vortex interaction over the W40C60 configuration at a 20 deg AOA is illustrated in Fig. 18. It has been mentioned in Fig. 8 that, at this incidence, no vortex merging exists and the vortices interact by effective induced flow, which is similarly reported in a study by Er-El and Seginer [35]. Generally, the canard vortex induces downwash flow near the apex of the wing, and the expansion of the wing vortex appears to be restricted until it develops into the upwash zone of the canard vortex: after which, the wing vortex expands faster in size and breakdown occurs.

Fig. 18 Interaction mechanism of the vortices at 20 deg AOA.
which has the same tendency with the identity of delta wings at sideslip. Therefore, it can be inferred that the vortex breakdown difference on the wing of the close-coupled canard configuration should be more distinctive than the single delta wing case.

The effect of the downwash zone difference can be further studied by contrasting the field of wash flow between 0 and 5 deg AOSs, as displayed in Fig. 20. In the plots, $U_w$ represents the vertical wash flow induced by both vortices, with blue denoting downwash. It can be judged through vorticity magnitude that, at this incidence, the strength of the canard vortex at 0.2 and $0.3c_{rw}$ does not exhibit an obvious distinction with or without sideslip, which results in wash flow with little difference in intensity. Hence, the influence of canard position shift is the most decisive, which translates the downwash field toward the leeward side. Under more sufficient downwash, the leeward wing vortex appears to be more concentrated than the zero-sideslip case while the windward vortex expands.

2. Influence on Prestall Wing Vortex

After experiencing asymmetric interaction, the wing vortex represents some peculiar behavior responding to sideslip. The axial velocity distribution along the wing-vortex core at a 20 deg AOA is given in Fig. 21. Unlike the axial velocity of the canard vortex (Fig. 9), which continues to drop, the axial velocity of the wing vortex, on the contrary, receives acceleration before abrupt depreciation upon vortex breakdown. This kind of variation has been proven in the same way by Das and Longo [36]. The main finding here is that, under sideslip, due to the extension of the downwash zone on the leeward side, the leeward wing vortex possesses a longer chordwise range of core acceleration before breakdown (Fig. 21a). However, on the windward side, sideslip brings both a decrease in maximum axial velocity and promoted breakdown. The acceleration effect of the windward vortex core almost disappears at a 5 deg AOS (Fig. 21b). Seen from the variation of pressure coefficient at the vortex core, displayed in Fig. 22, increasing sideslip obviously weakens the minimum pressure of the leeward vortex, which is similar to that on the canard, but the pressure gradient before breakdown appears to be improved. As shown in Fig. 22a, even a favorable pressure gradient exists before vortex breakdown at a 5 deg AOS. On the windward side (Fig. 22b), sideslip-induced strengthening in the core pressure coefficient before vortex breakdown (Fig. 10b) is not identified, and the pressure of the vortex
**Fig. 22** Variation of pressure coefficient along wing-vortex core (20 deg AOA).

**Fig. 23** Surface pressure distribution at 30 and 60% wing root chord (20 deg AOA).

**Fig. 24** Contour of $\Delta C_p$ on wing at 20 deg AOA (blue denotes windward lift superiority).
core the vortex core experiences stronger pressure recovery than the leeward side, indicating a weaker wing vortex.

The consequent surface pressure distributions on the wing at 0.3 and 0.5$c_{w}$ are shown in Fig. 23. Recalling the pressure features on the canard displayed in Fig. 12 finds that the variation of the windward suction peak is in the same manner of that on canard, with wider, more inboard, but lower suction. Nevertheless, the leeward suction peak demonstrates a distinctive feature, as the width is heavily squeezed by the concentrated vortex shown in Fig. 20, which also induces higher suction upon increasing sideslip.

3. Cause of Unusual Rolling Moment

To directly show lift difference, subtraction of the pressure coefficient is again undertaken between the windward and leeward sides. Seen from Fig. 24, the demarcation line mentioned above also exists between lift superiority areas of the windward and leeward sides, which respectively, stands inboard and outboard of the line. Derived from Fig. 7a, at a 20 deg AOA, lift on the windward side is higher than the leeward side. This is revealed in the plots that although the windward lift superiority area shows a little deficit in the absolute value of Δ$C_{p}$ against the leeward side, its area appears to be more extensive, especially on the inner part of the wing.

However, difference shows that the demarcation line on the wing bends at some point, which differs from the relatively straight one on the canard. According to the preceding analysis, the bending is originated to the extended downwash zone on the leeward side that induces a more slender vortex and pushes the suction peak outboard, and the leeward wing vortex expands in the upwash zone. Therefore, the bending point (BP) of the demarcation line moves downstream as the AOS increases. It can also be inferred that the bending of the demarcation line helps to extend the windward lift superiority area but swallows the leeward superiority area before the BP. But, aft of the BP, due to sufficient delay of the leeward vortex breakdown, leeward lift superiority dominates the wing area outboard of the half-wingspan. Particularly in Figs. 24b and 24c, the superior leeward lift located outboard has a longer rolling-moment arm and overwhelms the moment generated by windward superior lift that is sited in the inner part of the wing. Thus, the unusual rolling moment toward the windward side that possesses lift superiority arises. In Fig. 24d, as the BP moves further downstream with the windward vortex expanding, the blue area grows to such a large scale that the windward side retrieves enough rolling moment and rebalances the configuration, as shown in Fig. 6. Conclusion can be made that, at this AOA, the shift of the BP on the demarcation line that is caused by asymmetric vortex interaction directly influences the rolling moment, and hence lateral stability.

4. Effect on Poststall Wing-Vortex Recovery

It has been shown in Fig. 8f that, under sideslip, the leeward vortex exhibits recovery from fully separated flow at a 30 deg AOA. The streamline plot in Fig. 25 provides a better view of this phenomenon. It can be seen that, at this incidence, the leeward canard vortex stays concentrated on both the canard and the wing, and formation of the concentrated wing vortex occurs under a tilted canard vortex trajectory. But, on the windward side, the canard vortex suffers destruction on the canard surface and the trailing canard vortex is merged into a zone of fierce separation on the wing, which remains disorderly, as it initially is under zero sideslip.

The contour of the wash flowfield, displayed in Fig. 26, explains the mechanism of leeward vortex recovery. From plots of the zero-sideslip condition, the effect of downwash flow generated by the canard vortex on the reattaching separated shear layer can be clearly identified, as the shear layer bends downward in the blue downwash region. When sideslip is present, both the strength and position of the canard vortex change simultaneously. As discussed in the last paragraph, the leeward canard vortex appears to be much stronger than the windward one; and in Fig. 26, the intensity of downwash flow on the leeward side is higher than the windward side. Accumulating the effect of the downwash zone extension on the leeward side that still stands out here, the leeward vortex is recovered by enhanced reattachment. On the contrary, reattachment of the shear layer on the windward side still gets weakened under a weaker downwash that shifts away.

Figure 27 shows the extremely asymmetric lift resulting from leeward vortex recovery. It is apparent that the leeward suction induced by the recovered wing vortex is so strong that red occupies all areas near the leading edge and no demarcation line exists anymore.
It should also be noted that merely a 1 deg AOS is able to cause a significant difference in pressure distribution, which is considered to be unique on a poststall close-coupled canard configuration, since it is due to enhanced vortex interaction. The resultant enormous positive rolling moment directly leads to loss of lateral stability, and it should be remembered in close-coupled canard aircraft design.

IV. Conclusions

Vortex flow over the W40C60 close-coupled canard configuration at a high AOA has been simulated using delayed detached-eddy simulation. At zero sideslip, predictions of force and pressure are in excellent agreement with the experiment within the full range of AOAs investigated. Under sideslip, notable nonlinearities are discovered, and investigations on vortex dynamics and canard/wing-vortex interaction reveal the origin. The main findings are summarized as follows:

1) The effect of sideslip on aerodynamic forces differs significantly upon different AOA regimes. Divergence in lateral stability from a statically stable state of low incidence appears at a 20 deg AOA and, at a 30 deg poststall AOA, positive sideslip induces enormous an unstable rolling moment, which causes abrupt loss of lateral stability.

2) Sideslip brings asymmetry to both canard and wing-vortex dynamics. The windward vortex suffers promoted vortex breakdown but possesses an expanded vortex core and inboard shifted position, also with higher swirl velocity before breakdown. The leeward vortex acts oppositely. The resultant imbalanced forces can be displayed by a featured demarcation line that exists on both the canard and the prestall wing, dividing the upper surface into two zones, where each side has superior lift, respectively. Variation of the sideslip and AOA will change lift superiority on both sides of the demarcation line, yet in different mechanisms and amounts. At a 20 deg AOA, the extension of the low-pressure area due to windward vortex core expansion results in superior windward canard lift against the leeward side; but, relatively low pressure retained due to delay of leeward vortex breakdown is the main motivation that leeward canard lift surpasses windward at a 30 deg AOA.

3) The trajectory of the canard vortex is tilted under sideslip, which brings asymmetric vortex interaction. The leeward wing vortex goes through more sufficient downwash, which strengthens the restriction of vortex core expansion and encourages further difference in vortex breakdown against the windward side. The consequence is reflected on the downstream movement of the bending point on the demarcation line upon increasing sideslip, which is responsible for the unusual rolling moment toward a higher lift side at a 20 deg AOA. At a poststall AOA, sideslip-induced asymmetric vortex interaction helps the single-sided recovery of the leeward vortex by strengthened reattachment of a separated shear layer, which finally causes an enormous unstable rolling moment.

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References


Fig. 27 Contour of ΔCp on wing at 30 deg AOA (red denotes leeward lift superiority).
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