Open-Type Separation on Delta Wings for Leading-Edge Bluntness

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A numerical simulation was carried out corresponding to recent experiments using delta wings with sharp and blunt leading-edges, which indicates the second primary vortex, at NASA Langley Research Center. However, the experimental data did not reveal the detailed physical phenomena regarding the second primary vortex, because the experiment used only on-the-body-surface data. In the present study, the physical phenomena were revealed using Reynolds-averaged Navier-Stokes computations with three one-equation turbulence models on an unstructured hybrid mesh. The adaptive mesh refinement method in the vicinity of the vortex center was also applied to have more mesh resolution. Consequently, the result quantitatively revealed that appropriate modeling regarding turbulent kinematic viscosity was significant. Moreover, the three-dimensional visualization of the computational fluid dynamics results suggested that the second primary vortex was a developing shear layer merging into an open-type separation generated late by the primary vortex.

Key Words: Delta Wing, Leading-Edge Separation, Bluntness Effect, Open-Type Separation

1. Introduction

Delta wings have been used for both space and supersonic transports because of their high aerodynamic performance. These transports utilize leading-edge separation at high angles of attack for take-off and landing. Analyses of the leading-edge separation have been performed in many experiments and computations. There have been many previous numerical studies of the leading-edge separation around a delta wing, for example, Ekaterinaris and Schiff,1) and Murayama et al.2)

The recent experiment at NASA Langley Research Center investigated the effects of leading-edge bluntness.3,4) In this experiment, sharp and three-type blunt leading-edges were used. The sharp leading-edge produces a typical conical vortex structure, with a suction peak occurring at almost the same semispan locations for the entire wing due to leading-edge separation, whereas the blunt leading-edge produces a more complex flow. This leading-edge delays the leading-edge separation onset downstream and another suction region appears inboard of the primary vortex. This suction peak was designated as the ‘second primary vortex’ by Luckring.3)

The objective of this study is to investigate the second primary vortex through computational fluid dynamics (CFD) analysis and its visualization, and to find out the second primary vortex. The experiment did not reveal detailed physical phenomena. Due to the high Reynolds number range in the experiment, three one-equation turbulence models were examined with an adaptive mesh refinement method in the vicinity of the vortices.

2. Computational Method

In this study, an unstructured mesh method5–7) was used to simulate the flow field. The three-dimensional Navier-Stokes equations were computed with a finite-volume cell-vertex scheme. An unstructured hybrid mesh method8) was applied to capture the boundary layer accurately and efficiently. The Harten-Lax-van Leer-Einfeldt-Wada Riemann solver9) was used for numerical flux computation. Venkatakrishnan’s limiter10) was applied for reconstructing the second-order accuracy. The lower-upper symmetric-Gauss-Seidel implicit scheme11) was applied for time integration.

Furthermore, in the unstructured hybrid mesh method, an adaptive mesh refinement method was used to increase the mesh resolution in the vicinity of the vortex centers.12) The vortex-center identification method13) identified the vortex centerlines accurately and efficiently as the distinct topological flow feature leading to the mesh refinement. In the region of tetrahedral unstructured mesh, a tetrahedral bisection algorithm was used.14,15) The prisms were refined along the normal-to-surface direction to preserve the structure of the mesh in case hanging nodes were located on the edges of the prisms.

3. Turbulence Models

It is essential for accurate prediction of the leading-edge separation vortex at high Reynolds numbers not only to stifle numerical diffusion, but also to consider the influence of turbulence modeling. Therefore, the influence of turbulence models should be examined carefully.

In this study, the Goldberg-Ramakrishnan (G-R) one-equation model,16) the Spalart-Allmaras (S-A) one-equation model,17) and modified S-A one-equation model proposed...
The geometries used in this study were based on the wind tunnel models described by Luckring. They correspond to sharp and blunt leading-edge shapes at a sweep angle of 65 deg. This study focused on the blunt leading-edge named the ‘medium-radius leading-edge’ by Luckring. Figure 1 shows the delta wing geometries with the sharp and blunt leading-edges for the present numerical simulation. The leading-edge of this wing was defined with an NACA-like airfoil polynomial for four values of leading-edge bluntness $n_{0}/c_{bar}$ of 0.0015. This leading-edge contour matched the flat-plate wing at 15% of the root chord and was constant spanwise to match the flat-plate central portion of the wing. The flat-plate portion of the wing extended back to 90% root chord, and the nondimensional wing thickness $t/c_{bar}$ was 0.051. Aft of the 90% root chord, the wing thickness smoothly diminished to a sharp trailing edge. The flow conditions were a Mach number of 0.4, an angle of attack of 13 deg, and a Reynolds number of 6 million based on the wing mean aerodynamic chord.

The bluntness effect is discussed with flows around sharp and blunt leading-edges. The unstructured hybrid mesh was generated, and then the adaptive mesh refinement method was applied to improve the mesh resolution in the vicinity of the vortex center. Figures 2(a) and 2(b) show the vortex centerlines and their neighboring cells, respectively, for the case with a sharp leading-edge. Figure 2(c) shows cross-flow plane views of the initial and refined meshes at the 60% root chord location. Figure 3 shows similar views generated for the case with a blunt leading-edge. The comparison of all mesh numbers is summarized in Fig. 4. A large increase in the number of tetrahedron indicates that the mesh resolution was mainly improved in the vicinity of the vortex center.

4. Results

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4.1. Adaptive refinement and turbulence model effects in the case of a sharp leading-edge

Computed surface pressure distributions were compared at 40 and 60% of the root chord location (Figs. 5 and 6, respectively). As shown in Figs. 5(a) and 6(a), the adaptive mesh refinement improved the suction peak of the primary vortex. Although the position of the suction peak was predicted correctly, its value did not agree well with the experiment. The computed pressure distribution at the inboard wing shown in Fig. 6 also did not agree well with the experi-
ment, because no sting fairing was modeled in this computation. These figures indicate that the adaptive refinement has a limitation to capture the suction peak quantitatively on the unstructured mesh.

To improve the numerical prediction of the suction peak, the original and modified S-A turbulence models were applied in addition to the laminar flow computation as shown in Figs. 5(b) and 6(b). The suction peak appeared poorest among the computations in the case of the laminar flow simulation. When no turbulence model was used, the expression of turbulent production was insufficient. Therefore, the primary vortex occurred weakly at the inboard-wing location rather than at the appropriate position. As the primary vortex did not severely bear on the secondary and tertiary vortices, they grew redundantly, and the pressure distribution became wavy, as shown in Fig. 6(b). The original S-A model showed similar performance to the G-R model. As shown in Fig. 5(b), the modified S-A model was found to predict the suction peak much better than the others. Figure 6(b) shows that the modified S-A turbulence model also captured the suction peak of the secondary vortex. The corresponding surface streamlines in Fig. 7 indicate the secondary separation as well as the tertiary separation.

The modified S-A model improved the production and destruction terms of the turbulence transport equation of the original S-A model. These two terms were examined to identify the key influence to capture the secondary separation. Figure 8 indicates that the production term had an influence, while the destruction term did not.

According to the modification in Eq. (1a) for the produc-
tion term of the transport equation, the value of the eddy viscosity becomes smaller in the vortical region. Figure 9 shows comparisons of contours at a cross-flow plane and isosurfaces of the computed eddy viscosities between the original and the modified S-A models. The modified S-A model captured the detailed vortex structure and restrained the amount of eddy viscosity. That is, appropriate modeling regarding the turbulent kinematic viscosity is the effective key for capturing complex vortex flow.

4.2. The second primary vortex in the case with a blunt leading-edge

The experiment suggested that the blunt leading-edge delays primary separation downstream and that another suction region, referred to as the second primary vortex, appears inboard of the primary vortex from 40% to 60% of the root chord location. Therefore, the computed surface pressure distributions at 20, 40, and 60% of the root chord location in the case with a blunt leading-edge were compared with the experimental data in Fig. 10. As the characteristic flow depends on chordwise location, the detail is discussed at each position as follows.

Figure 10(a), corresponding to the 20% root chord location, reveals that the laminar computation forms the primary vortex too early. A turbulence model is needed because turbulence models predict the attached flow near the wing apex. This figure shows that all turbulence models capture the attached flow near the wing apex.

Luckring suggests that the flat pressure distribution from the 70% to 90% spanwise location corresponding to the x-axis in Fig. 10(b) is a tribute of the origin of the second primary vortex. The modified S-A model showed a relative-
ly flat pressure distribution, indicating formation of the second primary vortex. Although the distribution does not agree well with the experiment and CFD results, the modified S-A model successfully predicted the position of the suction peaks of the first primary and secondary vortices. Figure 11 shows that the modified S-A model restrains the swell of the eddy viscosity and the detailed vortex structure better than the original S-A model.

Figure 10(c) shows the pressure distributions at the 60% root chord location. Although Luckring suggests that the second primary vortex ends in the vicinity of the 60% root chord location, the CFD results do not capture the suction peak. Furthermore, the CFD results do not correspond to the experiment near the leading-edge, as shown in Fig. 10(c). It is considered that the spanwise location of the vortices produced is different from the experiment, because the influence of vortex production is weak due to the production term in the modified S-A model, and the CFD resolution is insufficient to capture the detailed vortex phenomena. Figure 12 shows the computed surface streamlines and pressure distribution using the modified S-A model. The region of the pressure plateau shown in Fig. 10(b) was found at 35% to 57% of the root chord location. The chordwise location of the second primary vortex agreed well with the experiment because it suggests that the second primary vortex occurred from 40% to 60%.

Figure 13 shows the vortex structure using helicity contours at the cross-flow plane. This figure shows that the first and second primary vortices rotate in the same direction. Figure 14 shows a comparison of the streamlines close to the surface and through the second primary vortex. This figure indicates that streamlines near
The wall at the wing apex flow straight downstream, while streamlines inside the boundary layer merge into the second primary vortex. Figure 15 reveals that the shear layer occurs from the leading-edge because the helicity breaks out from the edge. Separation occurs in the middle of the blunt leading-edge. Figure 16 shows a sketch of the separation and streamlines near the blunt leading-edge. This figure suggests that the present separation on the blunt leading-edge is classified as open-type separation.

A brief explanation regarding an open-type separation is described as follows. In an open-type separation (or free-vortex layer-type separation), the separation line is not closed in the front leeside surface and does not originate or terminate at singular points where both skin friction components vanish; the limiting streamlines on both sides of the
separation line originate from the same front attachment (stagnation) point. In contrast, for closed-type separation, the separation line is closed around the body. It passes through the singular points of the limiting streamlines and the limiting streamlines on two sides of the separation line originate from the front and rear attachment points, respectively. In this study, open-type separation occurs, depending on the leading-edge bluntness and the delicate angle of attack.

Over the front part of the body, one would expect that the flow will be similar to that over a blunt cone or cylinder.22) The flow from the bottom body (shown by streamline 1 in Fig. 16) due to the angle of attack goes around the leading-edge toward the rear part of the body. Then, the streamlines merge into the open-type separation line due to the primary vortex. Because the flow on streamline 1 is accelerated due to the effect of the leading-edge bluntness, a shear layer occurs in region A shown in Fig. 16. That is, the second primary vortex suggested in the experiment was found to be a developing shear layer merging to the open-type separation line. Although the shear layer is common in open-type separation, the present shear layer (i.e., the second primary vortex on a delta wing) is rare and is produced as a result of the combination of the geometry of the leading-edge bluntness and flow condition. In the case of the sharp leading-edge, the separation is closed-type separation because the separation line always starts from the wing apex. Thus, the flow has a typical conical structure.

5. Conclusion

A numerical simulation around delta wings with sharp and blunt leading-edges was performed on an unstructured hybrid mesh with adaptive mesh refinement in the vicinity of the vortex center to investigate the second primary vortex effect due to the leading-edge bluntness suggested by experiment through three-dimensional CFD visualization. As a result, adaptive refinement to capture the suction peak quantitatively is limited. A modified Spalart-Allmaras one-equation turbulence model was found to be the most accurate to capture the complex vortex structure including the secondary vortex. This indicates that appropriate modeling regarding the turbulent kinematic viscosity is essential. This model captured the second primary vortex successfully as indicated in the experiment. The visualizations of the computational results suggest that this second primary vortex is a developing shear layer merging into the separation. This separation due to the leading-edge bluntness is classified as open-type separation, while the separation due to the leading-edge sharpness is classified as closed-type separation.

The second primary vortex suggested by the experiment occurs under particular conditions such as the geometry of leading-edge bluntness and angle of attack.

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References