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Observation of the Vortex Interaction over an Yawed Delta Wing with Leading Edge Extension by Flow Visualization and 5-hole Probe Measurements

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가시화와 5공 프로브 측정을 통한 연장된 앞전을 갖는 편요된 델타형 날개에서의 와류 상호작용 관찰

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Key Words: delta wing(델타형 날개), leading edge extension(연장된 앞전), vortex core(와류 중심), vortex interaction(와류 상호작용), yaw(편요)

Abstract

An experimental study is conducted to investigate the interaction of vortices over a delta wing with leading edge extension(LEX) through the off-surface flow visualization and the 5-hole probe measurements of the wing wake region. Especially, the application of a new visualization technique is employed by ultrasonic humidifier water droplet and laser beam sheet. The results, both the off-surface visualization and the 5-hole probe, show that LEX tends to stabilize the vortices of the delta wing up to the high angle of attack even though the model is yawed. With increasing yaw, the windward leading edge vortex moves inward, and closer to the wing surface, while the leeward vortex moves outwards and away from the wing surface. The vortex interaction is promoted in the windward side, and is delayed in the leeward side.

1. Introduction

The vortical flow field over a sharp-edged delta wing has been a subject of extensive research in modern combat aircraft aerodynamics. At moderate to high angles of attack, the wing upper surface pressure induced by the leading edge vortex provides a significant vortex-lift increment needed in an enhanced maneuverability of high performance combat aircraft. As the angle of attack increase, the leading edge vortices are strengthened, and the lift of the delta wing increases until a critical angle of attack is reached, where the vortices break down resulting a dramatic loss of lift, a sudden change of pitching moment, and buffeting. Sometimes the leading edge vortex pair on starboard and port sides of the wing break down asymmetrically, which causes the dynamic stability problem such as a sudden change of rolling moment direction and self-induced oscillating motion.

The delta wing having the leading edge extension(LEX) or the strake is known to have better aerodynamic performance than the delta wing alone configuration, especially at the higher angles of attack. At high angle of attack the strong LEX vortex induces a lateral velocity field which energizes the boundary layer on the wing upper surface where the flow has separated from the main wing leading edge. This stabilizes the main wing vortices and delay vortex breakdown to a higher angle of attack.

The yaw angle makes the vortical flow field in the wake region of the delta wing at high angle of attack more complex one. The wing side leading into the flow(windward side) has an effective decrease in sweep

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angle, whereas the wing side trailing(leeward side) has an effective increase in sweep angle. The decrease in effective sweep will cause stronger vortices, but it will also increase the likelihood of vortex breakdown. The vortex breakdown occurs at lower angles of attack, the asymmetry of the vortex pair is pronounced, and the dynamic stability is seriously deteriorated. Up to now the yaw is known to be most influential parameter causing the asymmetric vortex development and breakdown, and the dynamic stability problem of a sharp-edged delta wing or a highly swept slender wing. However, there are not much data available about the vortex flow over the yawed delta wing. Recent studies of the yawed delta wing and the delta wing with LEX are documented in references 1-5.

The present experimental study investigates the vortex interaction of the yawed delta wing with LEX through the off-surface flow visualization and 5-hole probe measurement of the wing wake region. The angles of attack range from 16 degree to 28 degree, and the yaw angles treated are 0 , -10, -20 degree. The free stream velocity is 40 m/sec for the 5-hole probe measurement, which corresponds to a Reynolds number per meter of 1.76×10^6 based on the wing centerline chord. The free stream velocity is 6.2 m/sec for the off-surface visualization, which corresponds to a Reynolds number per meter of 0.44×10^5.

2. Experimental Model and Technique

Fig. 1 shows the Delta wing/LEX model used in this study. The wing model is a flat type wing having a sharp leading edge. It has the 65 degree sweepback angle with 600 mm root chord without LEX and 795 mm with LEX, and 475.4 mm span at the trailing edge. The coordinates used in this investigation are x(streamwise), y(spanwise) and z(wing surface normal). The origin of the coordinate system is the apex of the delta wing.

The present experiment is conducted in two facilities. The first is the medium-sized subsonic wind tunnel of the Korean Air Force Academy that has a test section of 3.5 m(W)×2.45 m(H)×8.7 m(L). The total pressure and velocity vectors are measured in this wind tunnel by the use of 5-hole probe. The total pressure and velocity vectors are obtained at the 30%, 43%, 60% and 80% chord station. The five hole probe used has a nose diameter of 3.175 mm, and 30.48 mm long. The 5-hole probe is calibrated by employing the non-nulling method. The detailed description of wing model and 5-hole probe calibration data was presented in reference 6.

The off-surface visualization is made in the another KAFA small size subsonic wind tunnel[0.9 m(W)×0.9 m(H)×2.1 m(L)] by ultrasonic humidifier water droplet and laser beam sheet. The visualization data are obtained through the 1/6 reduced model. The laser light sheet is used to interrogate specific cross section of the vortical flow. This is particularly useful in determing the detailed arrangement of the vortices. The laser light sheet is created by passing the beam of an argon ion laser of 3 W through a cylindrical lens. The laser sheet is positioned perpendicular to the wing surface. Only the water droplets passing through the laser sheet are made visible. Thus, this offers the opportunity to visualize a cross-section of the vortical flow field only a few millimeters thick.

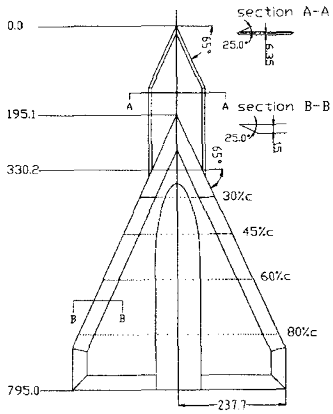


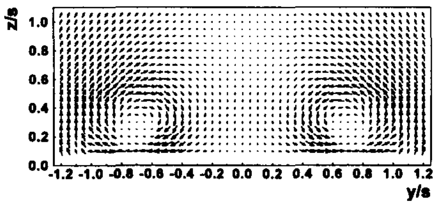
Fig. 1 Geometry of experimental model

3. Results and Discussion

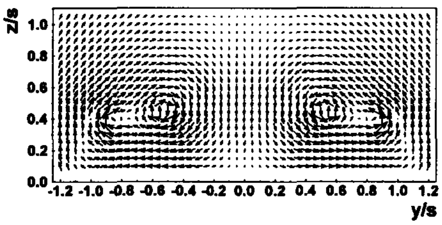
3.1 Effect of LEX and Vortex System of the No Yaw Case

The LEX introduces another pair of vortices in the wake region over the upper wing surface. The LEX and wing vortices have the same sign on each side of the wing. Fig. 2(a) shows the wing vortex pair in the wing wake region for the delta wing only configuration without yaw, represented by cross flow velocity vector. The angle of attack is 24° , and the wake section is 43% chord station from the wing apex. A concentrated and symmetric vortex pair is observed. Fig. 2(b) shows the vortex system of the delta wing/LEX configuration. The angle of attack and the chord station are same as those of Fig. 2(a). The vortex pair generated by LEX is located inboard upper space and the vortex pair generated by the main wing is located outboard lower space. The core position of the wing vortex is about y/s=0.86 and z/s=0.40 for the starboard side of the wing, s being the local semi-span.

Fig. 3 shows in detail the vortex system of the delta wing/LEX configuration by total pressure coefficient contour. The total pressure coefficient is defined as $C_{pt}=(P_t-P_{t\infty})/q_\infty$, where P_t is the total pressure of a point, $P_{t\infty}$ is the total pressure of the free stream, and q_∞ is the dynamic pressure of the free stream. Therefore, total pressure coefficient of the present study is considered as the total pressure loss in the vortex. The gradient of the total pressure field is related to vorticity by Crocco's theorem, and the iso-total pressure lines are used commonly to represent a vortex, which is a kind of concentrated vorticity.



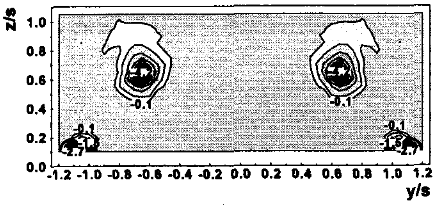
(a) LEX-OFF model



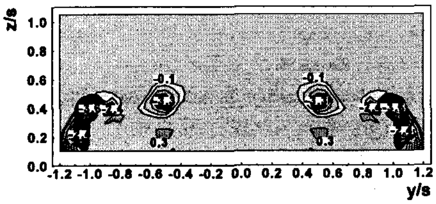
(b) LEX-ON model

Fig. 2 Cross flow velocity vector of the wake section for the LEX-OFF and LEX-ON model without yaw(α =24 degree, x/c=0.43)

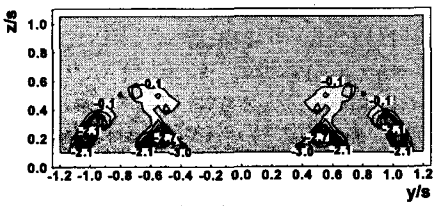
At the 30% chord station. the core position of the wing vortex of the starboard side is about y/s=0.96 and z/s=0.20 , and the core position of the LEX vortex of the starboard side is about y/s=0.63 and z/s=0.57. So the LEX vortex is at distance from the wing vortex when it enters the wing wake region. At the 43% chord station, the LEX vortex is moved to inboard and downward, and the wing vortex is moved inboard and upward by mutual induction of vortices having the same direction of rotation in each side of the wing. So the vertical position of the LEX vortex and the wing vortex are nearly same, and lateral distance of the two vortices is decreased much. It was observed that the relative position of these two



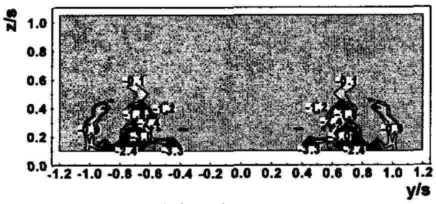
(a) x/c=0.3



(b) x/c=0.43



(c) x/c=0.6

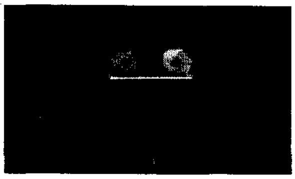


(d) x/c=0.8

Fig. 3 Total pressure contour of the LEX-ON model without yaw (α =24 degree)

vortices makes a unique pressure distribution on the wing upper surface at 30% chord and 43% chord stations, which is characterized as mild pressure gradient in the span direction and the inboard movement of suction pressure peak[7]. Fig. 3(b) also shows that the wing vortex is connected with the wing leading by the shear layer, which is the feeding path of vorticity and causes strengthening of the wing vortex at 43% chord station. At the 60% chord station the LEX vortex and the wing vortex are on the verge of coalescing at about 0.6 span position, and at the 80% chord station they merge completely to make one concentrated vortex. This merge of two vortices at downstream chord station brings a come back of the suction pressure peak of much increased strength on the wing upper surface. The approach speed and coalescing chord station was observed to depend on angle of attack and yaw angle.

Fig. 4 shows the visualization photos of the cross-sectional view of the wake region at the same chord station as that of Fig. 3. It is surprising to see that the fundamental structure of the vortex system is same for the two cases even though the model size and free stream velocity of Fig. 3 and Fig. 4 are much different. A small-sized wing vortex pair is observed at the position very close to the wing leading edge, and a large-sized LEX vortex pair is observed to exist inboard and upward position at the 30% chord station. At the 43% chord station, the LEX vortex is moved more inboard and downward, and the wing vortex is moved inboard and upward. By this movement the LEX and the wing vortices are close to each other and elongated in span direction. The downward movement of the LEX vortex and the upward movement of the wing vortex continues at downstream chord station. At 60% chord station, the core of the wing vortex is above the core of the LEX vortex as observed in Fig. 4(c). It was observed in the continuous section photos that the core of the LEX vortex is above the core of the wing vortex again by its moving outboard and upward after the 60% chord station before they reach the 80% chord station where the vortices completely merge. This inter-winding of the LEX vortex and the wing vortex is also observed in other studies[1, 3].



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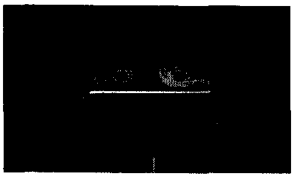
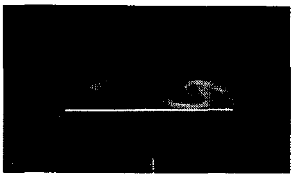
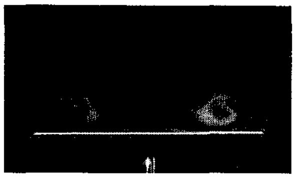


(b) x/c=0.43

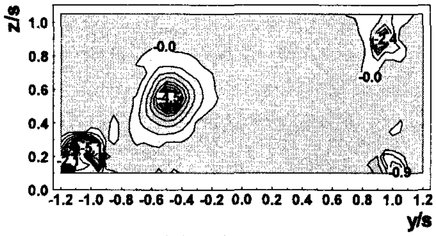


(c) x/c=0.6

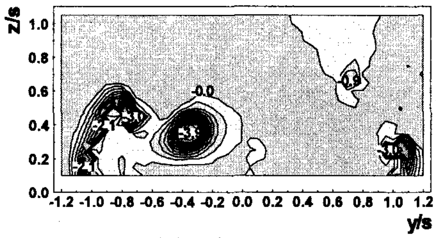


(d) x/c=0.8

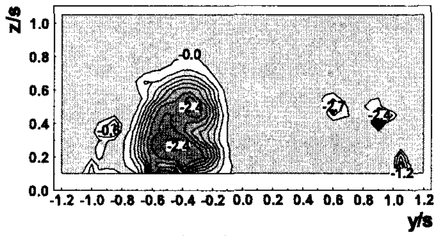
Fig. 4 Off-surface visualization photo of the LEX-ON model without yaw (α =24 degree)



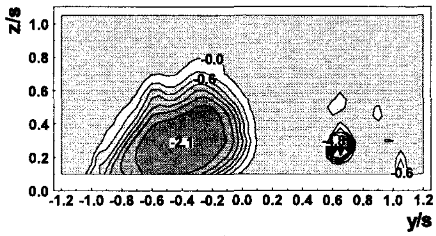
(a) x/c=0.3



(b) x/c=0.43



(c) x/c=0.6

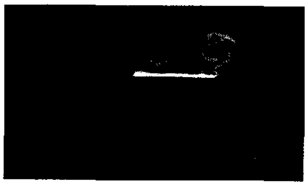


(d) x/c=0.8

Fig. 5 Total pressure contour of the LEX-ON model with yaw (α =24 degree)

3.2 Vortex Interaction of the Yawed Case

The vortex system of the yawed case are shown in Fig. 5 and Fig. 6. The yaw angle of -10 degree completely destroys the symmetry of the vortex pair which was preserved in the no yaw case. The LEX vortex of the windward side(left side) moves inboard and closer to the wing surface, while the LEX vortex of the leeward side(right side) moves outboard and away from the wing surface when they enter the wing wake region as observed in Fig. 5(a). The strengths of the LEX vortex and the wing vortex of the windward side are increased, but those of the leeward side are decreased much compared to the no yaw case of Fig. 3.



(a) x/c=0.3

(b) x/c=0.43

(c) x/c=0.6

(d) x/c=0.8

Fig. 6 Off-surface visualization photo of the LEX-ON model with yaw (α =24 degree)

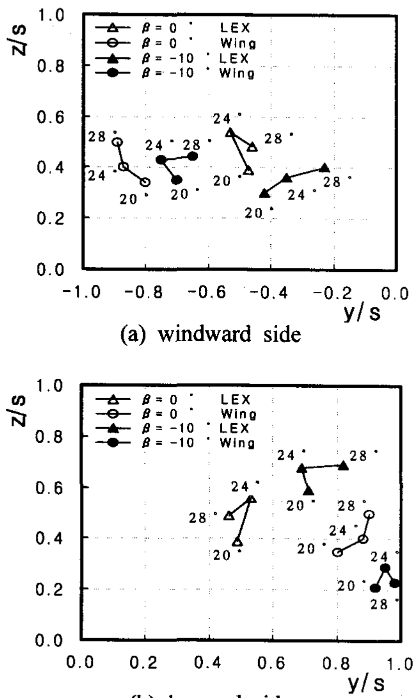
The relative movement of the two vortices in each side of the wing for the yawed wing case has the same tendency as for the case of no-yawed case. However, in the yawed wing case the interaction and merging process is promoted in the windward side, and it is delayed in the leeward side. It is observed in Fig. 5(c) that the LEX and the wing vortices of the windward side are completely merged in a diffused state, while those of the leeward side are not merged yet.

The visualization photo of the wake section of Fig. 6 shows the vortex system and the interaction of vortices of the yawed delta wing in more detail. The LEX vortex of the leeward side enters the wing wake region with greater distance from the wing surface and outboard station, while the LEX vortex of the windward side is closer to the wing surface as can be seen in Fig. 6(a). A careful examination of Fig. 6(a) shows that the wing vortex of the windward side is bigger than the wing vortex of the leeward side at the 30% chord station. This phenomenon is also observed in Fig. 5(a) of total pressure contour.

The LEX and the wing vortices of the windward side are completely merged at the 60% chord station, while those of the leeward side are not merged even at the 80% chord station. This means that the vortex interaction is suppressed in the leeward side of the yawed delta wing. The not-merged state of the LEX vortex and the wing vortex of the leeward side at the 80% chord station observed in Fig. 6(d) is different from the state of merged and concentrated vortex of Fig. 5(d), which is the vorticity field represented by the total pressure contour. This discrepancy is thought to be due to the large difference between the free stream velocities of the two cases. At large free stream velocity of Fig. 5 case, the interaction of the LEX and the wing vortices of increased strength is pronounced.

3.3 Vortex Interaction of the Yawed Case

The traces of the vortex cores at different angles of attack are compared in Fig. 7. The chord station is selected at 43% where complete merge or breakdown does not occur even at the highest angle of attack, 28 degree. The position of vortex core is assumed to be the position of the maximum absolute value of total pressure coefficient. In the windward side(Fig. 7(a)), the core of the LEX vortex and the core of the wing vortex of the yawed case are present at more inboard and downward position than those of the no yaw case. As the angle of attack increases, the LEX vortex moves inboard for both of the no yaw case and the yaw case. However, the wing vortex of the yawed case moves outboard at 24 degree and moves back inboard at 28 degree. The overall moving direction of the vortices at higher angles of attack is clockwise in the windward side where the vortices have the clockwise sense of rotation. In the leeward side, the yaw moves the LEX vortex more outboard and away from the wing surface, and the wing vortex outboard and closer to the wing surface as can be seen in Fig. 7(b). The moving direction of the LEX and the wing vortices at higher angles of attack is counterclockwise for the no yaw case, but it is clockwise for the yaw case. Therefore, the moving direction of the vortices of the yaw case is opposite to the sense of rotation of vortices in the leeward side.



(a) windward side

(b) leeward side

Fig. 7 Traces of vortex cores for different angles of attack

4. Conclusion

An experimental study is conducted to investigate the interaction of vortices over a delta wing with leading edge extension(LEX) through the off-surface flow visualization and the 5-hole probe measurements of the wing wake region. The angles of attack range from 16 degree to 28 degree, and the yaw angles treated are 0 , -10, -20 degrees. The free stream velocity is 40 m/sec for the 5-hole probe measurement. The free stream velocity is 6.2 m/sec for the off-surface visualization. The results show that LEX tends to stabilize the vortices of the delta wing up to the high angle of attack even though the model is yawed. With increasing yaw, the windward leading edge vortex moves inboard, and closer to the wing surface, while the leeward vortex moves outboard and away from the wing surface. The strengths of the LEX and wing vortex of the windward side are increased, while those of the leeward side are decreased. The vortex interaction is promoted in the windward side, whereas it is delayed in the leeward side.

Acknowledgement

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References

(1) Erickson, G. E., Schreiner, J. A., & Rogers, L. W., "On the Structure, Interaction, and Breakdown Characteristics of Slender Wing Vortices at Subsonic, Transonic, and Supersonic Speeds," AIAA Paper 1989, AIAA-89-3345.

(2) Verhaagen, N. G., "Effects of Reynolds Number on the Flow over 76/40-deg Double-Delta Wings," AIAA Paper, 1999.

(3) Olsen, P. E., and Nelson, R. C., "Vortex Interaction over Double Delta Wings at High Angles of Attack," AIAA paper 89-2191, July 1989.

(4) Verhaagen, N. G., and Naarding, S. H. J., "Experimental and Numerical Investigation of Vortex Flow over a Sidesliping Delta Wing," J. of Aircraft, Vol. 26, No. 11, 1989, pp. 971-978.

(5) Grismer, D. S., and Nelson, R. C., "Double-Delta-Wing Aerodynamics for Pitching Motions with and without Sideslip," J. of Aircraft, Vol. 32, No. 6, 1995, pp. 1303-1311.

(6) Lee, K., and Sohn, M., "Investigation of Vortex Interaction over a Delta Wing over a Delta Wing with the Leading Edge Extension," J. of KIMST, 2001, to be appeared.

(7) Sohn, M., Baek, S., & Lee, K., "An Experimental Investigation of the Vortex Flow and Aerodynamic Load Characteristics of the Delta Wing/LEX Configuration in Sideslip," J. of KSASS, 2001, to be appeared.