Effects of Leading Edge Separation Vortex of Flexible Structure Delta Wing on Its Aerodynamic Characteristics

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The aerodynamic forces and moments of a flexible delta wing in pitching motion were experimentally studied in a low-speed wind tunnel. Three types of flexible delta wing were investigated, the flexible parts of which were 44, 70 and 99% of the delta wing. Aerodynamic characteristics were different among the three types of flexible and completely hard delta wing, and it was found that the winding-up of the leading edge of the delta wing is the key factor for determining the leading edge vortex on the upper side of the wing and the pressure distribution on the windward side. Lift, drag, and pitching moment formed a hysteresis loop with an angle of attack in pitching motion, particularly in a region with a large attack angle, accompanied by leading edge vortex breakdown. The flow visualization of leading edge vortices was also carried out to explain the dynamic characteristics of the delta wings.

Key Words: Leading Edge Separation Vortex, Delta Wing, Pitching Motion, Aerodynamics, Flow Visualization

1. Introduction

A leading edge vortex of a delta wing is broken down under certain conditions, such as a large angle of attack, and its behavior in unsteady motion, such as pitching motion, brings complex aerodynamic characteristics. Therefore, many research studies of delta wings have been conducted from the middle of the previous century(1) – (9). On the other hand, even high-speed aircraft cannot avoid taking off and landing at a low speed near the ground. Such an aircraft with a delta wing sometimes has unstable motion due to an atmospheric perturbation, such as a gust, and particularly has a unique unstable flight called the wing rock. However, the research of a delta wing in unsteady motion near the ground has not been sufficient. Our previous studies of thick and thin delta wings in pitching or rolling motion near the ground(10) – (13), which were made of hard metal alloy and could not be deformed in airflow, clarified that the existence of the ground hastens a stall and increases a lift markedly, for example, to more than 50%. Recently, the flexibility of a wing has been expected to improve wing performance characteristics, and Gordon and Ismet reported a flexible delta wing(14). In this study, we focused on the dynamic performance characteristics of a thin delta wing in pitching motion, the part of which was made of flexible material and could be deformed. The results for the flexible delta wing are discussed in comparison with those for a hard delta wing, and the aerodynamic characteristics of the flexible delta wing are mainly discussed in conjunction with the flow visualization results for the behavior of leading edge separation vortices.

2. Experimental Apparatus

2.1 Experimental apparatus

Figure 1 shows the flexible structure delta wing connected to a manipulator in a low-speed wind tunnel. The swept-back angle of the leading edge of the delta wing was 60 degrees, and the span at the trailing edge was 180 mm with a root chord length of 156 mm, as shown in Fig. 2. The aspect ratio of the wing was 2.31, and the wing thickness was 2 mm. The manipulator of the parallel type(15) for producing the pitching motion of the delta wing was fabricated, which had six stepping motors for six degrees of freedom and could produce a various delta wing motions. Its flight posture was changed at a speed of 0.5 Hz using a sinusoidal function programmed on a microcomputer. The rod between the delta wing and the manipulator was equipped with the force balance developed for research. The small and compact force balance with a weight of 5.6 g could measure lift, drag and pitching mo-
ments. The force balance was ring-shaped, and the strain gages for drag and lift were pasted 39.5 and 90 degrees on the ring from the force balance axis, namely, the positions of symbols D and L, as shown in Fig. 3. The strains at these locations were theoretically not interactive in lift and drag measurements. Pitching moments were measured using the strain gages at the location of the symbol PM in Fig. 3. It was ascertained that the force balance measures lift, drag, and pitching moments within errors of 2.59, 2.04 and 2.58%, respectively, by validating previously obtained measurements.

2.2 Experimental procedure and conditions

The attack angle of the delta wing was $25 \pm 10$ degrees for pitching motion and ranged from 0 to 38 degrees for a static delta wing without the motion. The other experimental conditions are shown in Table 1. The leading edge vortices were visualized at the center of the gravity of the delta wing using an argon-ion laser sheet that lightened smoke clouds in the airflow to analyze the resultant aerodynamic characteristics of the delta wing, as shown in Fig. 4. The speed of the airflow should be reduced for the clear visualization of a leading edge vortex, preventing smoke from diffusing. It would not reveal essential phenomena under the low-speed freestream condition, because a flexible delta wing could not be sufficiently deformed by such airflow. The Reynolds and Strouhal numbers with flow velocity and root chord length became $1.04 \times 10^5$ and 0.0078, respectively. In addition to the hard delta wing in Fig. 2, three types of flexible delta wing were
Fig. 5 Three types of flexible delta wing with hard part of hatched portion: (a) A-, (b) B- and (c) C-type flexible delta wings

Fig. 6 Deformation of C-type flexible delta wing compared with that of hard delta wing. (a) C-type flexible delta wing and (b) hard delta wing

Table 2 Displacement of wing tip at trailing edge

<table>
<thead>
<tr>
<th>Angle of attack θ (deg)</th>
<th>A-type</th>
<th>B-type</th>
<th>C-type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>0 mm</td>
<td>5 mm</td>
<td>5 mm</td>
</tr>
<tr>
<td>25</td>
<td>2 mm</td>
<td>6 mm</td>
<td>15.5 mm</td>
</tr>
<tr>
<td>Dynamic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 (no motion)</td>
<td>1 mm</td>
<td>4 mm</td>
<td>6 mm</td>
</tr>
<tr>
<td>25 (down motion)</td>
<td>2 mm</td>
<td>6 mm</td>
<td>11 mm</td>
</tr>
<tr>
<td>35</td>
<td>3 mm</td>
<td>7 mm</td>
<td>16 mm</td>
</tr>
</tbody>
</table>

3. Results and Discussion

The aerodynamic characteristics of the three types of flexible delta wing in pitching motion are shown in Figs. 7–9, in which the results obtained under static conditions without pitching motion are also indicated. The coefficients of lift, Cl, drag, Cd, pitching moment, Cpm, and ratio of lift to drag, L/D, are shown in (a), (b), (c) and (d), respectively in each figure. The arrows in the figures show the directions of the trajectories corresponding to the pitching motions of the delta wings. By comparing the results for the A-type flexible delta wing with those for the hard delta wing, the stall angle of attack is 32 degrees.
Fig. 7 Aerodynamic characteristics of A-type flexible delta wing: (a) lift coefficient Cl, (b) drag coefficient Cd, (c) pitching moment coefficient Cpm and (d) ratio of lift to drag L/D

for both cases under the static conditions. The Cl of the A-type flexible delta wing is about 10% lower than that of the hard delta wing in a region with an attack angle between 15 and 25 degrees. However, the Cd has similar values in both cases. As a result, the L/D in the range of the attack angle for the flexible delta wing results in aerodynamic performance characteristics inferior to those of the hard delta wing. Particularly at the attack angle of 5 degrees, the maximum difference in L/D is obtained, as shown in Fig. 7 (d). Although the maximum Cl, Cd and Cpm are similar in the A-type flexible and hard delta wings, the Cl, Cd and Cpm of the flexible wing are smaller than those of the hard wing under the pitching motion conditions. This is due to the following. Because the middle part of the A-type flexible delta wing is a wide and hard flat plate, as shown in Fig. 5 (a), the winding-up degree of both sides of the flexible wing is smaller than those of both sides of the B- and C-type flexible wings. Furthermore, since the hard leading edge of the A-type flexible delta wing extends to one-third from the apex, the leading edge vortex of the flexible delta wing should be the same and its effects on aerodynamic characteristics are similar to those of the hard delta wing. This indicates that the differences between the results for the flexible and hard delta wings are mainly due to the pressure on the windward side of the delta wing near the leading and trailing edge corner induced by wing bending up. The pressure on this side of the A-type flexible delta wing should be lower than that of the hard delta wing because of air flowing laterally to the leading edge due to the winding-up of the wing. Therefore, the A-type flexible delta wing produces the Cl and Cd coefficients smaller than those of the hard delta wing owing to the lower pressure of the flexible delta wing than that of the hard delta wing. With regard to the aerodynamic characteristics of the A-type flexible delta wing in pitching motion, the time lag of breakdown and the reconstruction of the leading edge vortex shifts the Cl, Cd, and Cpm loops to an angle of attack larger than the static results, as shown in Fig. 7.

Under the static conditions, the B-type flexible delta wing has a smaller stall angle of attack, namely, 30 degrees, than the hard delta wing, namely, 32 degrees. In contrast to the results for the A-type flexible delta wing, the Cl, Cd and Cpm of the B-type flexible delta wing are larger than those of the hard delta wing. These results originate from the roll-up of the leading edge of the B-type delta wing. The roll-up of the leading edge increases the effective angle of attack that strengthens the leading edge vortices. Therefore, the hysteresis loops of the Cl, Cd and Cpm of the B-type flexible delta wing become larger.
Fig. 8 Aerodynamic characteristics of B-type flexible delta wing: (a) lift coefficient $C_l$, (b) drag coefficient $C_d$, (c) pitching moment coefficient $C_{pm}$ and (d) ratio of lift to drag $L/D$

Fig. 9 Aerodynamic characteristics of C-type flexible delta wing: (a) lift coefficient $C_l$, (b) drag coefficient $C_d$, (c) pitching moment coefficient $C_{pm}$ and (d) ratio of lift to drag $L/D$
than those of the A-type flexible delta wing and produce an earlier stall, that is, earlier breakdown of the leading edge vortices. The effects of the winding-up leading edge of the B-type flexible delta wing at a small angle of attack are different from those at a large angle of attack, absolutely between the small and large stall angles. At a small angle of attack, the winding-up of the leading edge of the B-type flexible delta wing makes the leading edge vortex stronger together with the distribution of a higher pressure on the windward side of the B-type flexible delta wing than on that of the hard delta wing. This results in the higher Cl and Cd. On the other hand, an excessive roll-up leading edge makes the leading edge vortex weak at a large angle of attack, namely, the formation of the smaller leading edge vortex is similar to that in Fig. 10. The total effects of the leading edge vortex formed above the delta wing and the pressure distribution on the windward side of the winding-up flexible delta wing determined the characteristics of the flexible delta wing. The winding-up of the leading edge of the flexible delta wing at small angle of attack made the leading edge vortex strong and produced a high Cl and a high Cd. However, the excessive roll-up of the leading edge resulted in an opposite effect because of the formation of a weak leading edge vortex.

The stall angle of attack for the C-type flexible delta wing is the same as that for the B-type flexible delta wing, namely, 30 degrees, owing to the same reason mentioned above for the B-type flexible delta wing. Furthermore, the maximum Cl, Cd and Cpm of the C-type flexible delta wing are similar to those of the B-type flexible delta wing. The different results for the C-type flexible delta wing from the B-type flexible delta wing are recognized in the results of Cl and Cpm. The Cl of the C-type flexible delta wing, which is similar to that of the hard delta wing, is lower than that of the B-type flexible delta wing, and the hysteresis of Cpm of the C-type flexible delta wing becomes larger than that of the B-type flexible delta wing. These results are due to the larger deformation of the C-type flexible delta wing. The too excessively wound-up wing exhibits a smaller Cl than the B-type flexible delta wing owing to the weak leading edge vortex, as shown in Fig. 10.

4. Conclusions

The dynamic characteristics of the flexible delta wing in pitching motion besides under stable conditions were experimentally investigated by comparing them with those of the hard delta wing. The total effects of the leading edge vortex formed above the delta wing and the pressure distribution on the windward side of the winding-up flexible delta wing determined the characteristics of the flexible delta wing. The winding-up of the leading edge of the flexible delta wing at small angle of attack made the leading edge vortex strong and produced a high Cl and a high Cd. However, the excessive roll-up of the leading edge resulted in an opposite effect because of the formation of a weak leading edge vortex.

References

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