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Engineering Notes

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Experimental Investigation of Vortex Flow over an 80 Degree/60 Degree Double Delta Wing at Sideslip

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Introduction

THIN slender wings with highly swept and relatively sharp leading edges, such as delta wings, are employed for several modern aircraft. At moderate to high angles of attack, the flow over such wings separates at the leading edges, resulting in a steady and stable so-called leading-edge vortex flow.[1] Double delta wings are planforms that incorporate two distinct leading-edge sweep angles. The first part of the double delta wing, the strake, has a much higher sweep angle than the aft portion of the wing, the main wing. The fineness ratio of the double delta wing is defined as the length of the strake to the root chord of the complete wing.[2] The double delta wing has been shown to have better aerodynamic performance than a simple delta wing having the same sweep as the main wing of the double delta with comparable area.[3] The improved aerodynamic performance is due to the interaction of the vortices created by the strake and main wing. The strake vortices tend to stabilize the main wing vortices and delay vortex breakdown to a higher angle of attack than would be possible for a simple delta wing of the same sweep as the main wing.[4] The interactions of the strake and wing vortices also produce an increase in the nonlinear vortex lift produced by the wing. When a double delta wing is put into a sideslipping condition, the upper surface flowfield can become quite complex. In sideslip, each side of the wing experiences an effective change in sweep angle. The side leading into the flow will see an effective decrease in sweep angle, whereas the trailing side will see an effective increase in sweep angle. On a double delta wing this can result in very complex interactions.[5] The decrease in effective sweep will cause stronger vortices and increase the likelihood of vortex breakdown of the main wing vortex. At sideslip, vortex core bursting occurs over the wing at a lower incidence than zero sideslip, and so it is essential to qualify the influence of this phenomenon. The sideboard experiencing the increase in effective sweep will have weaker vortices and a greater possibility of strong interaction between the strake and wing vortex.[6] Because of the importance of this effect on the stability and control of the air vehicle, it was decide to investigate the effect of these complicated interactions on the lateral–directional characteristic of slender double delta wing in an experimental approach.

Experimental Apparatus

The double delta wing model, which was used throughout this investigation, was a flat plate with thickness t of 13 mm, which was beveled at a 30 deg angle from the lower surface resulting in sharp apex and upper surface leading edges. The trailing edge of the double delta wing was left unbeveled. Table 1 presents the geometry of the model tested.

To conduct the pressure measurement, 52 pressure-tapping points with a diameter of 0.6 mm were drilled on longitudinal and crosswise locations on the upper surface of the double delta model. Figure 1 shows the distribution of these pressure-tapping points. In Fig. 1, x and y are the distance from wing apex and s is the local wing semispan in millimeters. Surface pressure data acquisitions was performed by using scanivalves and pressure transducers. Because the number of pressure-tapping points was greater than 48, two scanivalves were employed.

The open-circuit wind tunnel used for these experiments had the interchangeable test sections, the standard size being 0.46 × 0.46 m and 1.2 m long. A two-motor drive system was used to enable good speed control to be maintained at the test section velocities as low as 1 m/s for low-speed instrument calibrations, and a maximum wind speed of 45 m/s could be achieved. Following the test section, the airstream was drawn through an eight-bladed axial flow fan and passed around a 90-deg corner with turning vanes, where it was discharged into the atmosphere. The delta wing under investigation

Table 1 Geometry of 80 deg/60 deg double delta wing

Strake sweep angle Λ_s, deg	80
Wing sweep angle Λ_w, deg	60
Shape of leading edge	Sharp
Strake root chord C_s, mm	127
Wing root chord C_w, mm	127
Model root chord C, mm	254
Fineness ratio $K_f = C_s/C$	0.5
Thickness ratio t/C, %	0.0512
Number of pressure taps	52
Maximum wing span b, mm	190
Model planform area S, mm^2	17780
Aspect Ratio $AR = b^2/S$	2.03

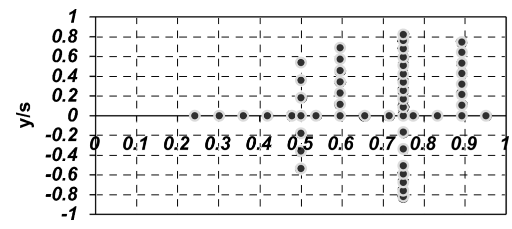

Fig. 1 Distribution of pressure-tapping points over 80 deg/60 deg double delta wing model.

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was installed at the midposition of the test section, and maximum velocity of 30 m/s was used for these experiments, which based on the centerline chord yields $Re = 4.8 \times 10^5$.

The surface oil-flow technique was intended to enable the nature of the flow over the whole of surface of the model to be investigated quickly and easily in the wind tunnel. The surface was coated with a specially prepared paint consisting of a fine powder mixed with a suitable liquid like oil or kerosene. The mixture was applied by hand on the upper surface using a brush. The air flowing over the surface carries the oil with it, and a streaky deposit of the powder remained to mark the direction of flow and the location of separation. For the surface oil-flow investigation, kerosene was used as the oil medium and titanium dioxide as the pigment. The mixture started to flow over the model surface at about 75% of the test speed and produced a fully developed pattern in about 2 min. The visualization information was photographed using a 35-mm camera from the top of test section. A 500-W lamp was placed on the top of the test section glass to perform the photography.

For laser light sheet flow visualization, the smoke was taken from the smoke generator of a laminar smoke wind tunnel. Then the smoke was conducted to the smoke probe placed in a far distance in front of the model inside the wind-tunnel test section.

The necessary equipment such as a three-dimensional traversing platform and laser light sheet were used, and the cross section of the vortices was eventually illuminated by a thin sheet of intense light produced by a 30-m · W helium–neon laser in conjunction with an optical system. The laser was mounted on a traversing platform enabling translation in all three directions. Through this, the streamwise development of the vortex flow from $x/c = 0$ to $x/c = 1.1$ was visualized. The flow patterns were photographed at different angles of attack α, ranging from $\alpha = 0$ to $\alpha = 30$ deg and also at different sideslip angles β, ranging from $\beta = 0$ to $\beta = -15$ deg. The flow visualization information was recorded on both photographic film and videotape. To visualize clearly the vortex flow by the laser light sheet flow visualization method, experiments had to be performed in the dark at night to avoid having any light other than the laser light for a black background. Just a small concentrated ray of light with adjustable brightness had to be directed through the top section glass to illuminate the model surface.

For surface oil and laser light sheet flow-visualization experiments, a very thin layer of black color adhesive paper was carefully applied to the upper surface to cover the pressure-tapping points located on upper surface of the model. Black was used to provide good contrast against the white powder (titanium dioxide) used for the oil-surface flow and so as not to reflect laser light.

Surface pressure data reduction essentially consisted of measuring the static pressure over the wing surface and plotting the pressure coefficient C_p, as a function of y/s for different angles of attack (0, 5, 10, 15, 20, and 30 deg) and different angles of sideslip (0, −5, −10, and −15 deg).

Discussion of Results

To study the effect of sideslip on the flow behavior over double delta wing model, it was decided to investigate the effect of angle of attack on this wing in zero sideslip first. As a result, flow-visualization experiments were conducted. As can be seen from the surface oil method shown in Fig. 2, the strake lines of the vortices of the strake and wing part are symmetrically situated over the surface of the double delta wing. Crosswise flowfield results were also obtained by laser light sheet flow visualization at low angle of attack, $\alpha = 5$ deg, and a medium to high angle of attack, $\alpha = 20$ deg. The core of the vortices over the wing and strake of the double delta wing were clearly observable. The vortices were located symmetrically over the wing and the strake.

The same situation was then applied for conducting longitudinal and crosswise surface pressure measurements. Figure 3a shows the effect of varying angle of attack on the pressure coefficient at the centerline of the model. As the angle of attack was increased from 0 to 30 deg, the centerline suction increased uniformly. However, for all of these angles of attack, the centerline suction dropped aft of the strake/wing juncture, which was located at $x/c = 0.5$, and then

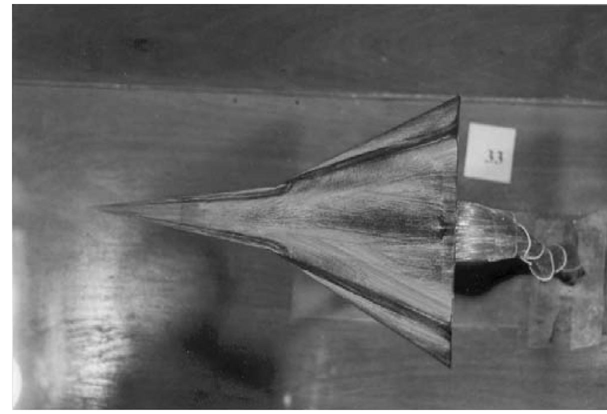

Fig. 2 Merging of strake vortex core into wing vortex core over 80 deg/60 deg double delta wing at $\alpha = 5$ deg, $\beta = 0$ deg, and $Re = 4.8 \times 10^5$.

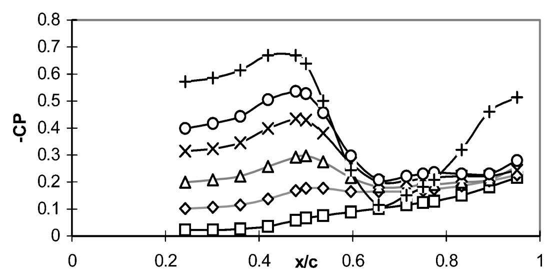

Fig. 3a Chordwise surface pressure distribution over 80 deg/60 deg double delta wing at zero sideslip, and $Re = 4.8 \times 10^5$: □, $\alpha = 0$; ◇, $\alpha = 5$; △, $\alpha = 10$; ×, $\alpha = 15$; ○, $\alpha = 20$; and +, $\alpha = 30$.

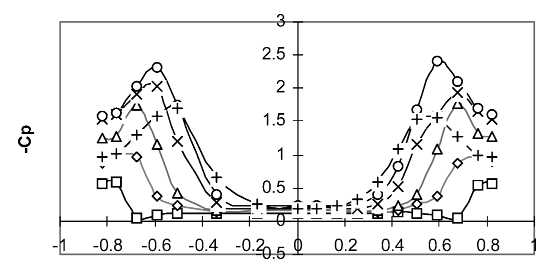

Fig. 3b Spanwise surface pressure distribution over 80 deg/60 deg double delta wing at zero sideslip, $x/c = 0.75$, and $Re = 4.8 \times 10^5$: □, $\alpha = 0$; ◇, $\alpha = 5$; △, $\alpha = 10$; ×, $\alpha = 15$; ○, $\alpha = 20$; and +, $\alpha = 30$.

started increasing with increasing angle of attack. For this sharp leading-edged double delta wing model, the wing and strake vortices coiled around each other after the strake/wing juncture, and the wing vortex trajectory then moved upward, in the z direction. That drop in the suction just aft of the strake/wing juncture and then slight increase in suction is due to this vortex behavior. For $\alpha = 30$ deg, the drop of suction peak is much more noticeable, which is a consequence of vortex breakdown that occurs at about $x/c = 0.7$ of the model.

Figure 3b shows spanwise surface pressure distribution for different angles of attack at zero sideslip measured in $x/c = 0.75$. It can be seen that for $\alpha \leq 20$ deg, the suction peak increased with increasing angle of attack on both sides of the wing, on the starboard side as well as the port side. It is a fact that those vortices are symmetrically occurring over the wing. Because of the vortex reattachment over the middle of the wing, the surface pressure does not vary much and has an approximately similar value for all angles of attack. For zero angle of attack, a small suction peak can also be observed for the strake vortex, which was symmetrically positioned inboard on each side of the wing. As the angle of attack increased, the wing vortex wrapped around the strake vortex, resulting in one suction peak on each side. At $\alpha = 30$ deg, the effect of vortex breakdown is that the

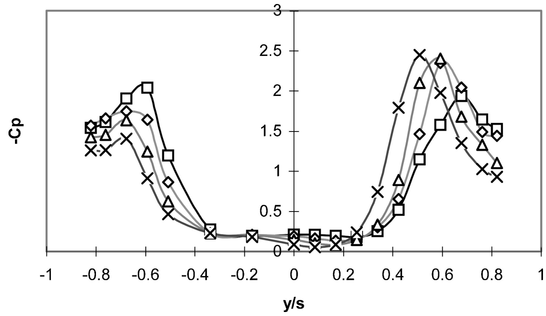

Fig. 3c Spanwise surface pressure distribution at $x/c = 0.75$ over 80 deg/60 deg double delta wing at $\alpha = 15$ deg and $Re = 4.8 \times 10^5$: □, $\beta = 0$; ◇, $\beta = -5$; △, $\beta = -10$; and ×, $\beta = -15$.

suction peak falls on both starboard and port sides of the double delta wing (shown in Fig. 3b). The two methods of visualization used in the experiment verified this explanation for this investigation.

To investigate the effect of sideslip, the model was installed at different sideslip angles; 0, −5, −10, and −15 deg. Figure 3c shows the surface pressure distribution for the those sideslip angles at a moderate angle of attack, $\alpha = 15$ deg. It is clear that the windward and leeward vortices are symmetric for $\beta = 0$ deg. However, with increasing sideslip angle, the windward strake and wing vortices have merged together and their suction peaks have moved toward the leeward side. With increasing sideslip, suction peaks of the vortices decreased near the central region of the wing. Leeward suction peaks also moved toward their leading edge. Suction peaks on the windward side were, however, stronger than on the leeward side. At nonzero sideslip angles, stronger vortices occurred on the windward side due to lower effective sweep angle. The cores of these vortices were also located closer to the model surface.

Conclusions

A series of qualitative and quantitative experimental investigations into the effect of angle of attack and sideslip on the aerodynamic behavior of a sharp leading-edge 80 deg/60 deg double delta wing were conducted. Surface oil-flow and laser light sheet visualizations, as well as surface pressure measurements, were performed on the strake and wing upper surface. The following observations are made.

1) Suction peak increases with increasing angle of attack symmetrically on both sides of the double delta wing before vortex breakdown occurs.

2) Increasing sideslip will cause strong asymmetric vortices over starboard and port sides of the wing, which causes different lift characteristics and as a result causes rolling moment. This may produce difficulties in stability and control of the wing.

Acknowledgment

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