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Nonuniform Motion of Leading-Edge Vortex Breakdown on Ramp Pitching Delta Wings

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Vortex flow characteristics on ramp pitching delta wings of sweep angles from 59 to 70 deg were studied by flow visualization and LDA measurement. Experimental observations indicate that the movement of the breakdown point is strongly dependent on the sweep angles and the pitching rates. The moving behavior of the breakdown point can be characterized by the occurrence of two delays. The first delay is due to the fact that the flow initially takes a length of time comparable to C/U_∞ to respond to the pitching motion. The second delay exists only for specific sweep angles and occurs in the course of pitching-up motion. It is characterized by the phenomenon that the breakdown point is moving slowly or even standing still above the wing surface for a certain length of time. The chordwise location corresponding to this occurrence shifts upstream as the pitching rate increases. This delay diminishes as the sweep angle increases. The LDA data obtained further reveal that both delays are associated with the underdevelopment of the primary vortex.

Introduction

RECENTLY, there has been increased interest in the maneuverability of both advanced fighters and missiles. The maneuverability typically includes both flight performance at higher angle of attack or yaw, and during transient motions.[1] The former can be achieved by choosing vortex-dominated devices, such as a single delta wing, a double delta wing, or a combination of a strake with a single delta wing.[2-4] The latter flight condition which is associated with the effect of transient motion of the vortical flow is not completely understood today. However, understanding such an effect is rather critical if one would like to develop a method for controlling vortex breakdown in maneuvering motion.

In previous reports, investigations of vortical flows on delta wings in transient motions were conducted under various experimental conditions. These conditions include a delta wing undergoing a sinusoidal motion[5-10] or a continuous ramp pitching-up and pitching-down motion,[11] and a delta wing undergoing a single ramp pitching-up or pitching-down motion.[11,12] Regardless of the wing motions performed, the characteristics of vortex breakdown phenomenon are of major interest in these studies. Jarrah,[9] Magness et al.,[11] LeMay et al.,[7] and Thompson et al.[12] showed that during the transient motions of the 75-deg-[9,11] and 70-deg-sweep[7,12] delta wings the moving speed of the breakdown point is nearly a constant, except near the minimum and maximum angles of attack, and can be normalized to a single value by the reduced frequency or reduced pitching rate. On the other hand, the unsteady characteristics of vortex breakdown after the completion of the transient motion of the delta wing were studied by Reynolds and Abtahi.[13] For a delta wing undergoing ramp pitching-up or pitching-down motion, they showed that the breakdown point takes a time longer than the convective time scale associated with the mean flow to relax to its final position. Reynolds and Abtahi[13] explained this phenomenon with a hypothesis that the propagation of vortex breakdown flow is governed by a solitary wave mechanism.

LeMay et al.[7] studied the hysteresis phenomenon of vortex breakdown for a delta wing in transient motion, and showed that in the case of sinusoidal motion the hysteresis loop on a plot of breakdown positions vs angles of attack gets enlarged as the reduced frequency increases. According to Thompson et al.,[12] for the case of single ramp pitching motion the delay angle in comparison with the angle of attack corresponding to the same location of vortex breakdown point on the stationary delta wing gets larger as the pitching rate increases. The effect of delay is also reflected in the aerodynamic force measurements. In the case of ramp pitching-up motion, Jarrah[9] noticed that an overshoot occurs in the curve of lift coefficients vs the instantaneous angles of attack. He suggested that this overshoot is due to the delay of propagation of vortex breakdown. Jarrah[9] further addressed the fact that this overshoot gets pronounced as the aspect ratio of the delta wings increased. He noticed that before the breakdown point appears at the trailing edge, the lift coefficients of the pitching delta wing coincide with those corresponding to the stationary wing.

The purpose of this study is to investigate the phenomenon of delay of vortex breakdown propagation on delta wings undergoing pitching motions. Physics of flow associated with this phenomenon is explored by the experimental techniques of flow visualization and laser-Doppler anemometry, respectively.

Experimental Facilities and Methods

Experiments were conducted in a low-speed water channel which was designed and built in the Institute of Aeronautics and Astronautics, National Cheng Kung University. The main structure of the water channel is made of 3-mm-thick stainless-steel plate, with a pump driven by a 20-hp ac motor. The test section, made of 15-mm-thick Plexiglas, has a cross-sectional dimension of 60 × 60 cm and a length of 250 cm. A porous plate is installed at the downstream end of the test section to keep the disturbances generated in the receiving tank from propagating upstream. Upstream of the contraction section a fine mesh stainless-steel screen was installed to reduce the turbulence level. The nonuniformity of velocity distribution in the test section surveyed by a hot-film probe is found to be

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below 2%, based on the maximum and minimum mean velocities measured in the core of the test section. The turbulence level of the flow measured is below 0.8%. Both flow-visualization and LDA (laser Doppler anemometer) measurements were conducted at a freestream velocity, denoted as U_∞, of 5.8 cm/s.

Four wing models are selected for the present study (see Fig. 1a for their geometrical dimensions). These models were cut from stainless-steel plate of 1 mm thick without any modification at the edge, namely, squarely sharp. The wing models are supported by a four-bar linkage mechanism, see Fig. 1b, which is similar to that reported by Gad-el-Hak and Ho.[5] The four-bar linkage mechanism is equipped with a ½-hp servomotor. The servomotor is linked with a 400:1 gear box which drives the four-bar linkage to perform desirable pitching motions. The instantaneous angle of attack of the tested delta wing is obtained from the voltage output of a variable electric resistance. As shown in Fig. 1c, the relation of pitching angle vs time appears to be very close to a linear-ramp function.

Experiments were performed with the techniques of dye-visualization and LDA measurement. Dye was prepared by mixing food color and water. The dye injection needle was glued beneath the wing surface with its outlet located approximately at the wing apex to reveal the characteristics of the vortex core. Straight lines were marked on the upper surface of each of the wing models which divide the entire chord length into 16 equally spaced sections, providing a reference frame for the location of the breakdown point.

Frequently the position of vortex breakdown is referred to as a location corresponding to rapid deceleration of velocity in the core, downstream of which a wake-type velocity distribution develops. This definition, however, is difficult to apply to the present flow-visualization results. Alternatively, an intrinsic character of the vortex breakdown phenomenon that the core of the vortex tends to diverge abruptly downstream of the breakdown point is adopted for identifying the vortex breakdown point. Thus, the vortex breakdown point can be inspected from the dye streak pattern. By this method, the breakdown point obtained from the video tape can be accurate to within 1/32 chord length.

The velocity measurements were conducted with a standard two-component, DANTEC 55X modular LDA system, which was equipped with a 5-W Argon-ion laser as the light source.

Table 1 Range of α for pitching-up and pitching-down motions of delta wings

Sweep, deg	Ramp up, deg	Ramp down, deg
59	12.5–28.5	23.5–10.5
63.4	15.5–35.5	—
67	15.5–38	—
70	21–41	41–21

The analog output of the LDA system is processed for velocity information.

Experimental Parameters

The experimental parameters considered include the reduced pitching rate K and the sweep angle Λ. K is defined as $\dot{\alpha}C/2U_\infty$ where $\dot{\alpha} = \mathrm{d}\alpha/\mathrm{d}t$ (rad/s) is the pitching rate, and C is the root chord length. The K values studied are confined in a range below 0.08.

In the case of pitching-up motions, the initial α selected is slightly less than the first critical angle of the vortex breakdown which occurs when the breakdown point appears at or slightly upstream of the trailing edge, depending on the sweep angles of delta wings. The final α selected is to be near or slightly over the second critical angle which occurs when the vortex breakdown point is situated near the wing apex. The ranges of α corresponding to the pitching-up motions of the four-wing models are listed in Table 1. The experiments of ramp pitching-down motion were made for wing models of 59-deg- and 70-deg-sweep angles only. The ranges of α selected for pitching-down motions are also given in Table 1. In reference to the conditions of the maximum α shown in Table 1, the blockage ratios of the delta wing models employed are limited below 0.06. As the delta wings undergo pitching motions, the freestream velocity measured by LDA at the cross-sectional plane 20 cm upstream of the tested model remains constant without noticeable variations with time.

Results of Flow Visualization

Vortex breakdown positions observed on stationary delta wings, in terms of the distance from the trailing edge, are documented in Figs. 2a–2d for reference. In this figure, the observed vortex breakdown positions vs α for four delta wing

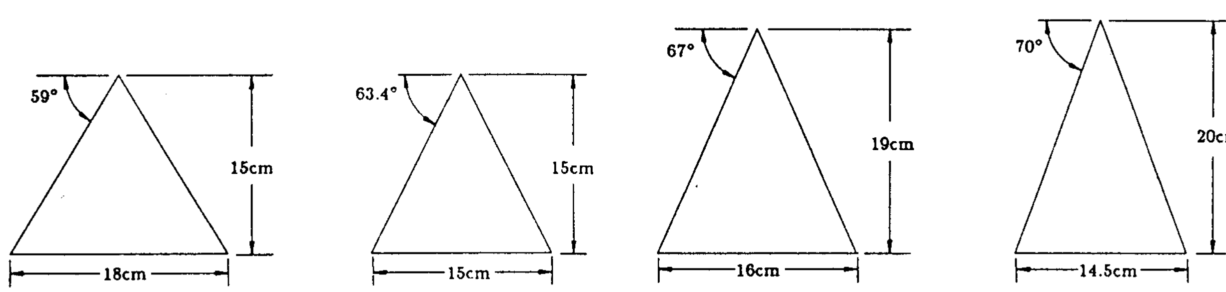


Fig. 1a Delta wing models for this study.

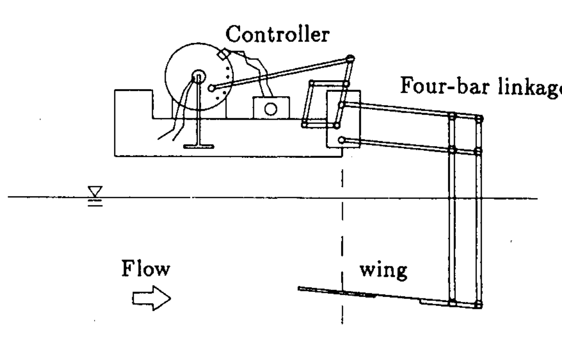


Fig. 1b Four-bar linkage mechanism.

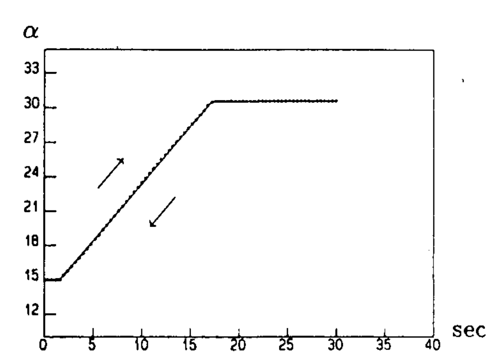


Fig. 1c Relation of the pitching angle vs time.

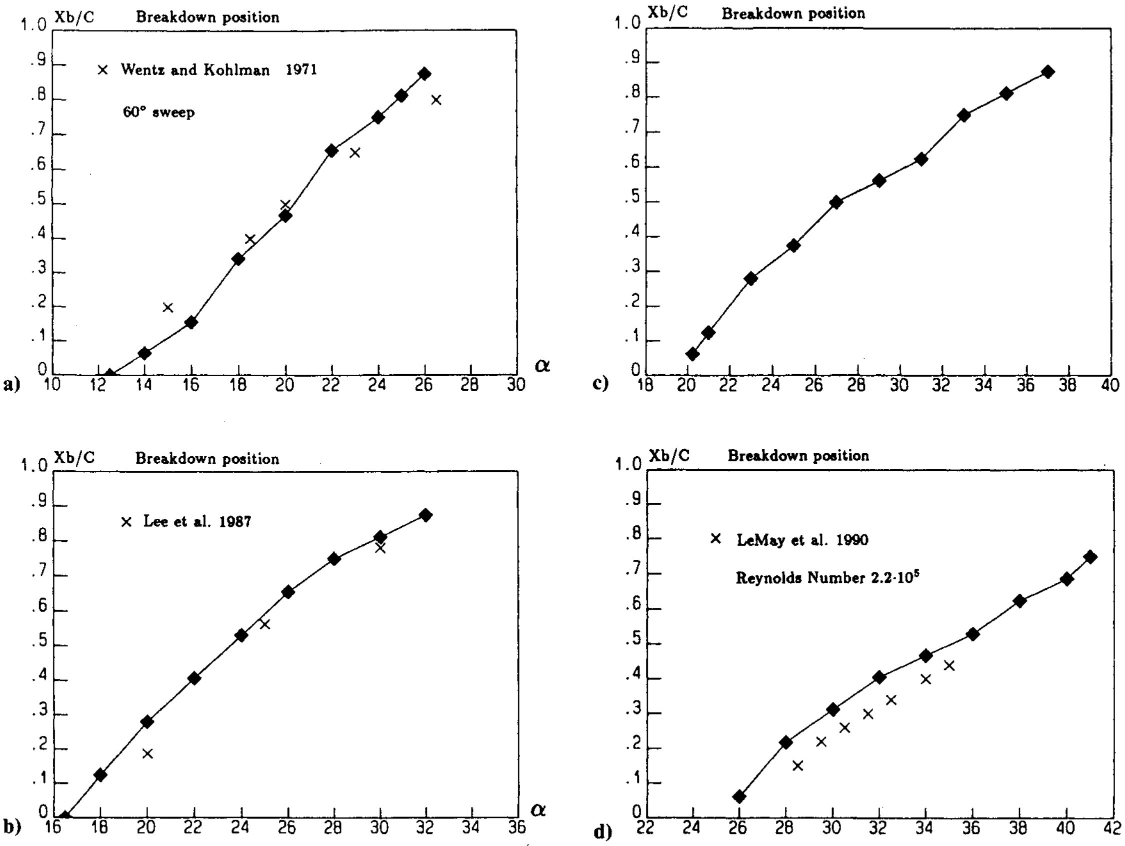


Fig. 2 Relations of vortex breakdown positions vs α for stationary delta wings: a) 59-deg sweep, b) 63.4-deg sweep, c) 67-deg sweep, and d) 70-deg sweep.

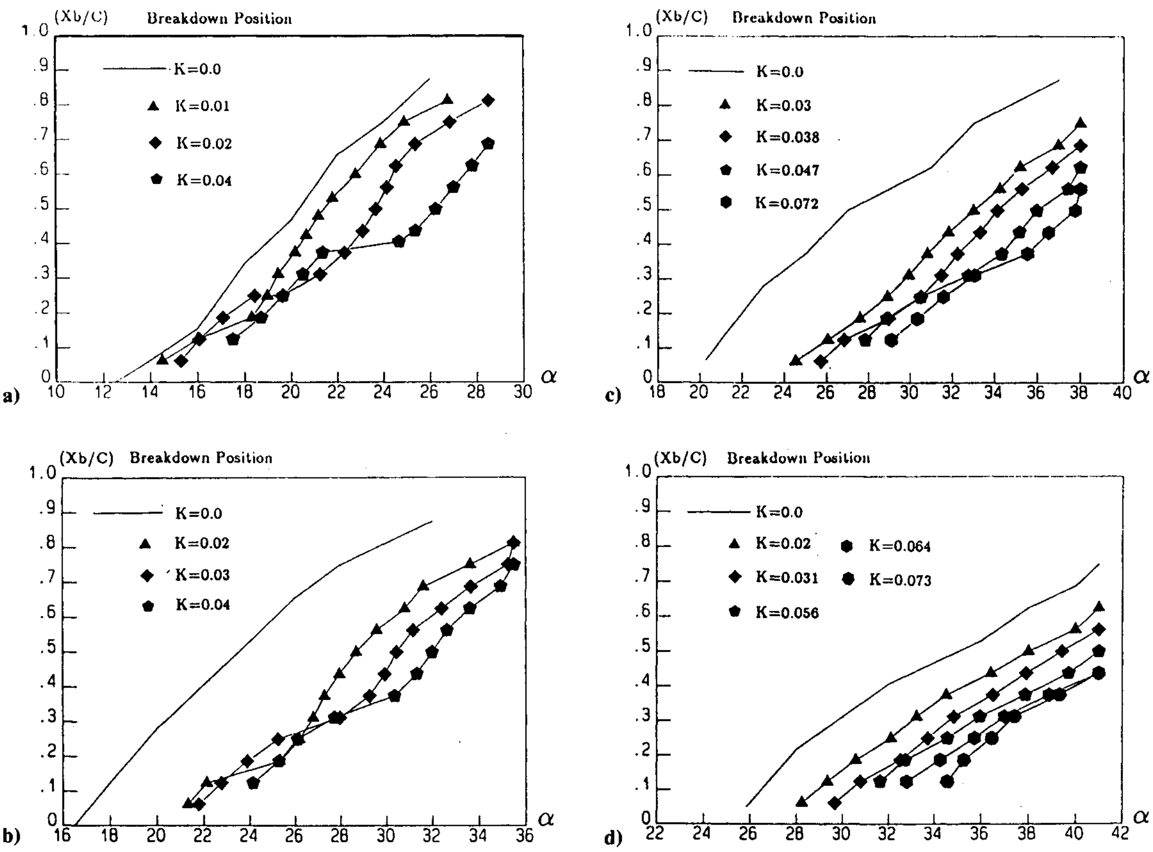


Fig. 3 Variations of the instantaneous vortex breakdown positions for different sweep delta wings in ramp pitching-up motion, pitch center at 1/2 chord length: a) 59-deg-sweep delta wing, at $Re = 9000$, $K = 0, 0.01, 0.02$, and 0.04; b) 63.4-deg-sweep delta wing, at $Re = 9000$, $K = 0, 0.02, 0.03$, and 0.04; c) 67-deg-sweep delta wing, at $Re = 11{,}000$, $K = 0, 0.03, 0.038, 0.047$, and 0.072; and d) 70-deg-sweep delta wing, at $Re = 11{,}000$, $K = 0$, 0.02, 0.031, 0.056, 0.064, and 0.073.

models are shown for Reynolds numbers from 7×10^3 to 1.7×10^4. The Reynolds number denoted as Re is defined based on U_∞ and C. X_b denotes the chordwise position of the vortex breakdown point where $X_b = 0$ is at the trailing edge of the delta wing. X_b is positive in the upstream direction. As can be seen in this figure, the results obtained in the present study are in good agreement with those reported by Wentz and Kohliman,[14] Lee et al.,[15] and LeMay et al.[7] for 59-deg-, 63.4-deg-, and 70-deg-sweep delta wings, respectively. This confirms that the present visualization technique can identify the vortex breakdown position above the delta wing reasonably accurately. It should be pointed out that for the 70-deg-sweep delta wing the breakdown point cannot occur exactly at the trailing edge.[12] However, for the cases of delta wings of lower sweep angles the location of vortex breakdown may occur very close to the trailing edge. For instance, as seen in Fig. 4, at $\alpha = 12.5$ deg which is the initial α for 59-deg-sweep delta wing in pitching-up motion, the vortex breakdown position is located approximately at the trailing edge.

Ramp Pitching-Up Motion

Figure 3a shows the relations between the vortex breakdown positions observed and the instantaneous α at $K = 0$, 0.01, 0.02, 0.04 for the 59-deg-sweep delta wing undergoing pitching-up motion, $Re = 9000$ with the pitching center at 1/2 chord length from the trailing edge. In this figure, it is interesting to note that when the value of K is not zero, the delay in the propagation of the vortex breakdown point is quite obvious in comparison with the solid curve of the stationary case. Furthermore, the delay is mainly attributed to two occurrences. The first delay takes place immediately after the delta wing is set into motion. Flow visualization indicates that the vortex breakdown point remains near the initial position for a certain length of time and then moves with a nearly constant speed. For instance, when $K = 0.04$ the vortex breakdown point observed at 0.25 chord length from the trailing edge is at the instant of $\alpha = 20$ deg, while for $K = 0$ the vortex breakdown point observed at the same chordwise position is at $\alpha = 16.5$ deg. Hence, a delay of 3.5 deg for the case of $K = 0.04$ is found. This figure also reveals a trend that this delay gets more pronounced as K increases.

When $K = 0.01$ and higher, an additional delay of vortex breakdown propagation, called the second delay, is noted during the pitching-up motion. As seen in Fig. 3a, upstream propagation of the vortex breakdown point may slow down or even hold still at certain α. For instance, in the case of $K = 0.04$, when α increases from 21 to 24.5 deg the vortex breakdown position remains at about 0.38 chord length from the trailing edge. An important feature revealed from the figure is that as K increases the chordwise position corresponding to this delay shifts upstream and the values of α corresponding to this delay get higher. Even for $K = 0.01$, the second delay is still discernible at the position about 0.13 chord length from the trailing edge, as α increases from 16 to 18 deg.

In Fig. 3a, it is also noticed that for each case of K the slope of the breakdown positions relative to the instantaneous angles of attack appears to be quite linear, except for the durations of the first and the second delays. Furthermore, the linear slope is comparable to that of the stationary case. These observations suggest that the nonuniform motion of the vortex breakdown position is mainly contributed to by the occurrences of delay in propagation of the vortex breakdown position.

Physical processes associated with the second delay at $Re = 9000$ for $K = 0.02$ and $K = 0.04$ are illustrated by the flow-visualization photographs given in Figs. 4 and 5, respectively. Referring to Fig. 3a, when $K = 0.02$ the second delay occurs at

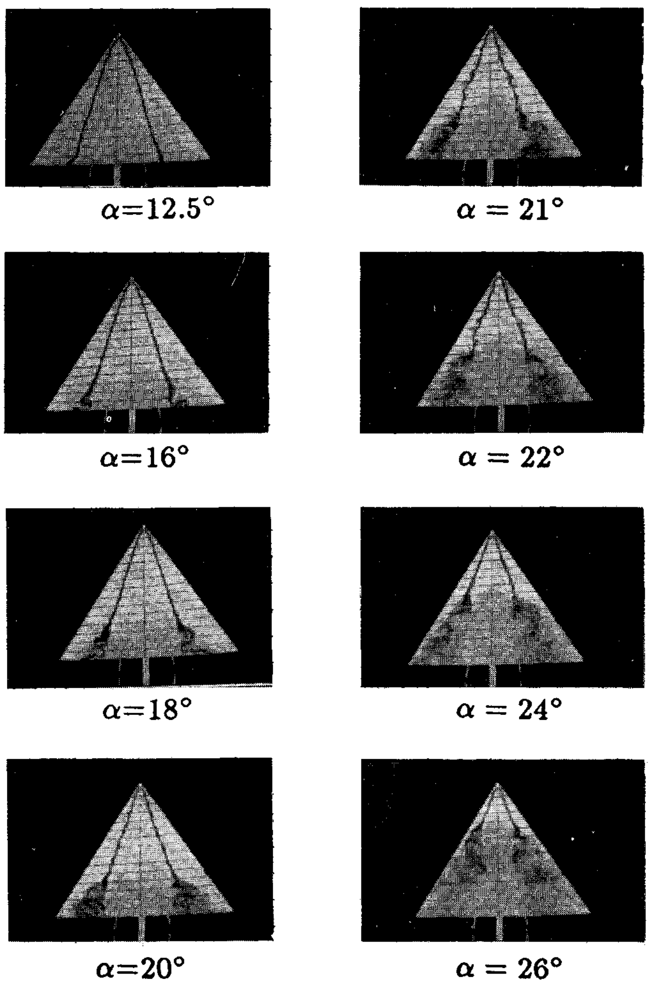


Fig. 4 Time-sequence flow-visualization photographs for 59-deg-sweep delta wing, at $Re = 9000$, pitch center at 1/2 chord length, and $K = 0.02$.

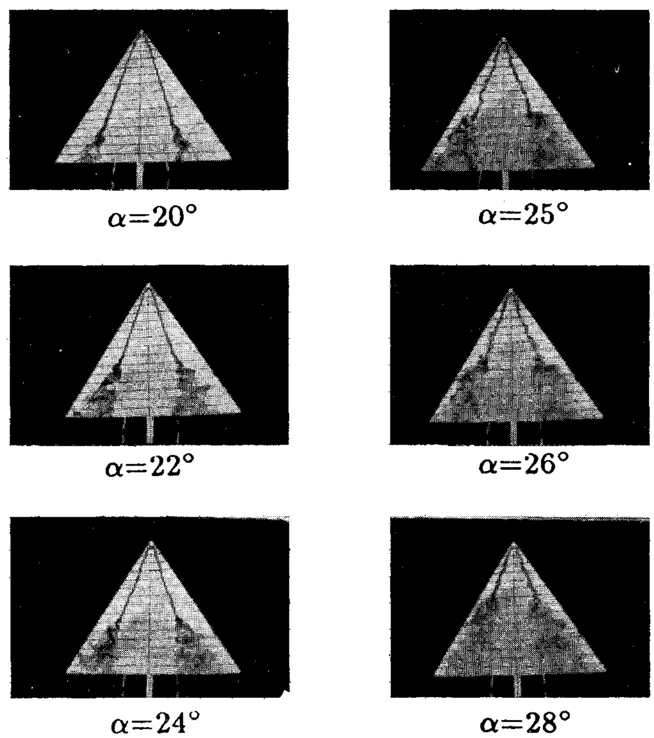
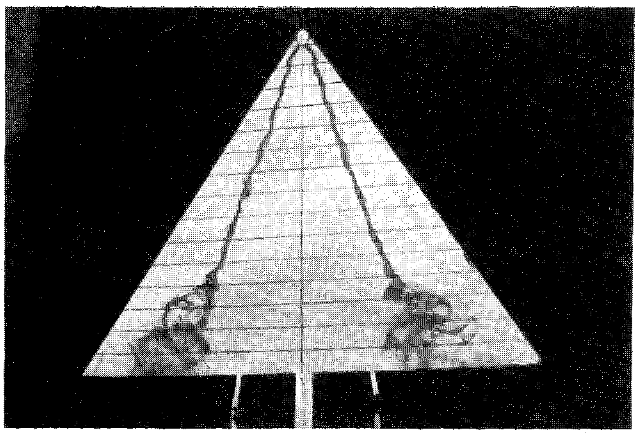


Fig. 5 Time-sequence flow-visualization photographs for 59-deg-sweep delta wing, at $Re = 9000$, pitch center at 1/2 chord length, and $K = 0.04$.

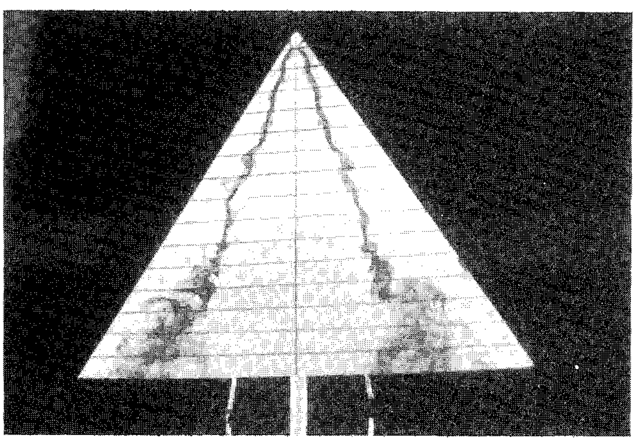
$\alpha = 18$ deg to 20 deg, and when $K = 0.04$ this delay occurs at $\alpha = 21$ deg to 24.5 deg. From Figs. 4 and 5, a feature in common noticed is that during the second delay the vortex core in the region upstream of vortex breakdown takes on a wiggling appearance, implying that some disturbances develop along the axis of the vortex core. Based on the findings of Gad-el-Hak and Blackwelder,[16] Payne et al.,[17] and Reynolds and Abtahi[13] on stationary and pitching delta wings, the disturbance observed could be due to the instability of the shear-layer shedding from the leading edges of delta wing. The enlarged photographs shown in Fig. 6 for $K = 0.02$ further reveal that near and after the end of the second delay, i.e., at $\alpha = 20$ deg and 21 deg, the disturbance develops to an extent that distorts the vortex structure severely. It should be mentioned that this distortion is of a three-dimensional manner. The side view of the flowfield shows that the trajectory of the vortex core is not straight in the chordwise direction, but gets distorted and lifts up from the wing surface as the delta wing undergoes pitching-up motion.

The phenomenon of second delay was studied for its dependence on the effects of initial α and sweep angle of the model. Speaking of the effect of initial α, flow-visualization results for the 59-deg-sweep delta wing show that the occurrence of second delay is still discernible until the initial α is increased beyond 18 deg. These experiments were performed with the final α held at 28.5 deg.

Flow-visualization results obtained for the other three delta wing models of higher sweep angles clearly show that the phenomenon of second delay is influenced by the geometries of the delta wing, see Figs. 3b–3d. While the effect of the first delay can be immediately realized from each of the figures, the phenomenon of second delay becomes less pronounced as the sweep angle of the delta wing increases. For instance, in the case of 63.4-deg-sweep delta wing (Fig. 3b), the second delay is noticed as a slowdown of the propagation of the breakdown point. The results of 67-deg-sweep delta wing shown in Fig. 3c indicate that the second delay phenomenon is hardly identifiable unless K is greater than 0.038. In the case of 70-deg-sweep delta wing (Fig. 3d), even at $K = 0.073$ the second delay effect is not found. Meanwhile, flow-visualization results of the 70-deg-sweep delta wing show that during the pitching-up motion the vortex core upstream of the vortex breakdown point does not distort as severely as that noted for the case of the 59-deg-sweep delta wing.

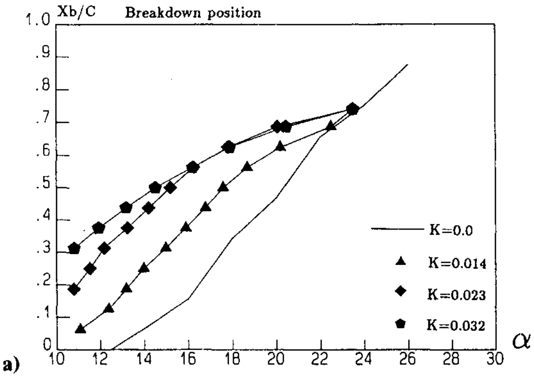


$\alpha = 20°$

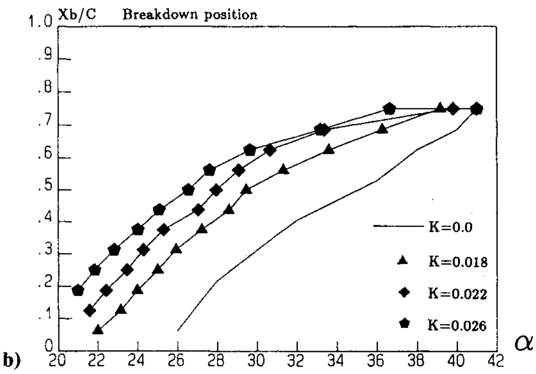


$\alpha = 21°$

Fig. 6 Enlarged flow-visualization photographs of $\alpha = 20$ deg and 21 deg in Fig. 4.



a)



b)

Fig. 7 Variations of the instantaneous vortex breakdown position: a) for 59-deg-sweep delta wing in ramp and pitching-down motion, at $Re = 9000$, pitch center at 1/2 chord length, $K = 0$, 0.014, 0.023, and 0.032; b) for 70-deg-sweep delta wing in ramp pitching-down motion, at $Re = 11{,}000$, pitch center at 1/2 chord length, $K = 0$, 0.018, 0.022, and 0.026.

Ramp Pitching-Down Motion

In the cases of ramp pitching-down motion, a delay in downstream propagation of the vortex breakdown point over the delta wing is noticed immediately after the wing is set into motion. Figures 7a and 7b show the relations of the vortex breakdown positions vs the instantaneous angles of attack for the 59-deg-sweep and 70-deg-sweep delta wings, respectively, for a number of pitching rates. It is apparent that the major delay occurs immediately after the wing is set into motion. After this delay, the slopes of the data for different cases of K follow the same trend as that of the stationary case indicated by the solid curve. Unlike the cases of pitching-up motion no additional delay is found in the pitching-down motion.

Qualitative Analysis

Experimental observations described above suggest that as the delta wing undergoes pitching motions, except for the

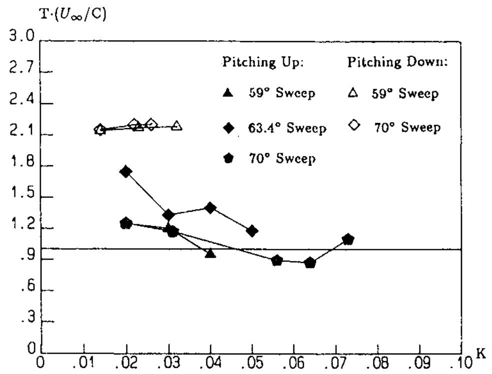


Fig. 8a Normalized time lengths of the first delay vs K.

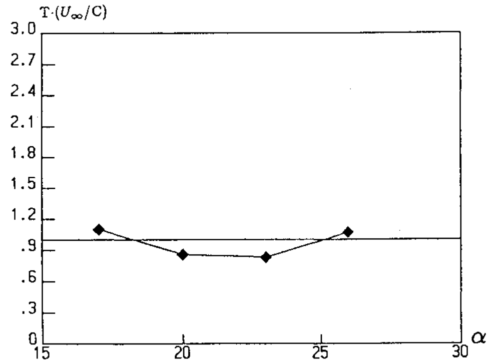


Fig. 8b Normalized time lengths of the first delay vs the initial α, for 63.4-deg-sweep delta wing in ramp pitching-up motion, at Re = 9000, K = 0.05.

moments corresponding to the occurrences of the first and second delays, the propagation speed of the vortex breakdown point is about constant. This finding is consistent with the observations reported by Thompson et al.[12] and LeMay et al.[7] for the 70-deg-sweep delta wing, and Jarrah[9] and Magness et al.[11] for the 75-deg-sweep delta wing. This flow behavior can be described mathematically as follows.

Except for the time durations of the first and second delays, the propagation velocity of the breakdown point, $U_s = \mathrm{d}X_b/\mathrm{d}t$, can be expressed as

$$U_s/U_\infty = 2r^*K \tag{1}$$

The constant r^* is dependent on the sweep angle which can be estimated from the slope of the vortex breakdown positions vs α in the stationary case. Normally, r^* falls in a range about 2–3. For the maximum K value studied in the present work, U_s is about $0.4U_\infty$, which is lower than the freestream velocity.

The time lengths corresponding to the first delay in pitching-up motions can be deduced from the delay angles measured and the pitching rates. For the cases of pitching-up motion, the delay angle is measured as the vortex breakdown point reaches the location $X_b = 0.12C$. On the other hand, for the cases of wings in ramp pitching-down motions, the delay angle is measured at the final stop of the motion. The time lengths of delay are then nondimensionalized by (C/U_∞) and are shown in Fig. 8a. It is interesting to note in this figure that the normalized time lengths corresponding to different wing models in pitching motions are about the same order of (C/U_∞).

In comparison with the case of the stationary wing, the delay angles measured due to the first delay in pitching motions can be approximated by the following expression.

$$\text{The delay angle due to the first delay} \approx (360/\pi)C^*K \text{ (deg)} \tag{2}$$

C^* is a constant coefficient, $1 \le C^* \le 2$.

The delay angle due to the first delay of vortex breakdown can also be obtained from the data published by Thompson et al.,[12] for a 70-deg-sweep delta wing performing pitching motions in the range of α between 30 and 40 deg, at Re of an order of 10^5. The pitching center was selected at 1/2 chord length from the trailing edge. In the ramp pitching-down cases, the delay angles corresponding to $K = 0.017$, 0.022, 0.026 are estimated to be 2.5, 3.2, and 4.0 deg, respectively. In the ramp pitching-up cases, the delay angles are estimated to be 1 and 1.5 deg corresponding to $K = 0.0067$ and 0.0087, respectively. These results agree with the predictions by Eq. (2).

A question raised by the present authors is that if the breakdown point initially is at a different chordwise position on a pitching delta wing, does the time length of the first delay remain of the same order? This question was studied by the experiments on the 63.4-deg-sweep delta wing model. The results shown in Fig. 8b indicate that the time scale of the first delay is insensitive to the initial location of the breakdown point for the initial α up to 26.5 deg.

Results of LDA Measurement

Surveys of the velocity field using an LDA system were carried out for delta wings in ramp pitching-up motions. The main purpose is to clarify the mechanism associated with the nonuniform motion of the vortex breakdown flow, notably the phenomenon of the first and second delays noticed in the flow visualization.

LDA measurements were performed over a cross-sectional plane shown in Fig. 9. This cross-sectional plane is across the pitching center. In Fig. 9, the X, Y, and Z axes employed for the present study are indicated. The X axis is parallel to the freestream direction. The Y axis is perpendicular to the X axis and is positive upward. The Z axis is parallel to the span of the test section. The coordinate system is fixed relative to the test section of the water channel. The origin of the axes is located at 1.5 mm above the pitching center. The X, Y, Z coordinates are normalized by the semispan of the delta wing model across the pitching center, denoted as S_0.

It is known that the LDA signals obtained describe the temporal velocity variations at the measured points while the delta wing is in unsteady motion. Therefore, utilizing these measured data to construct the spatial distribution of the

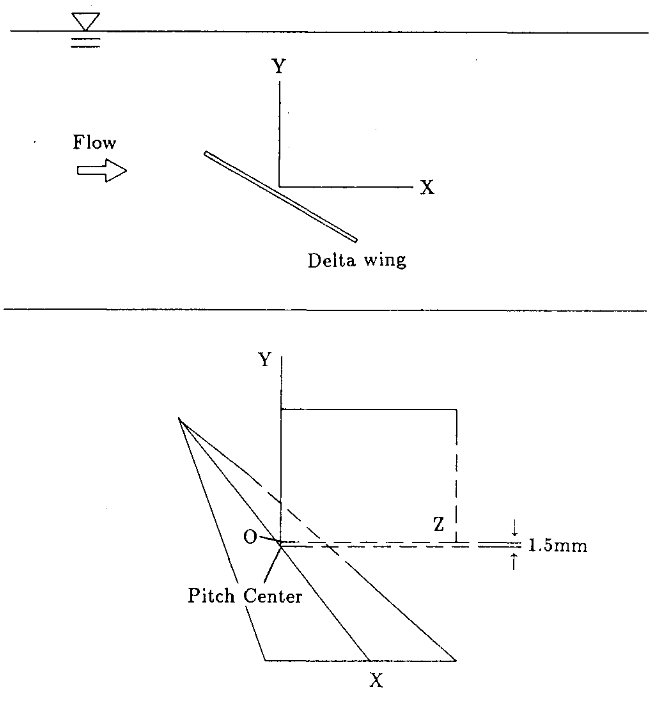


Fig. 9 Coordinate system for LDA measurement.

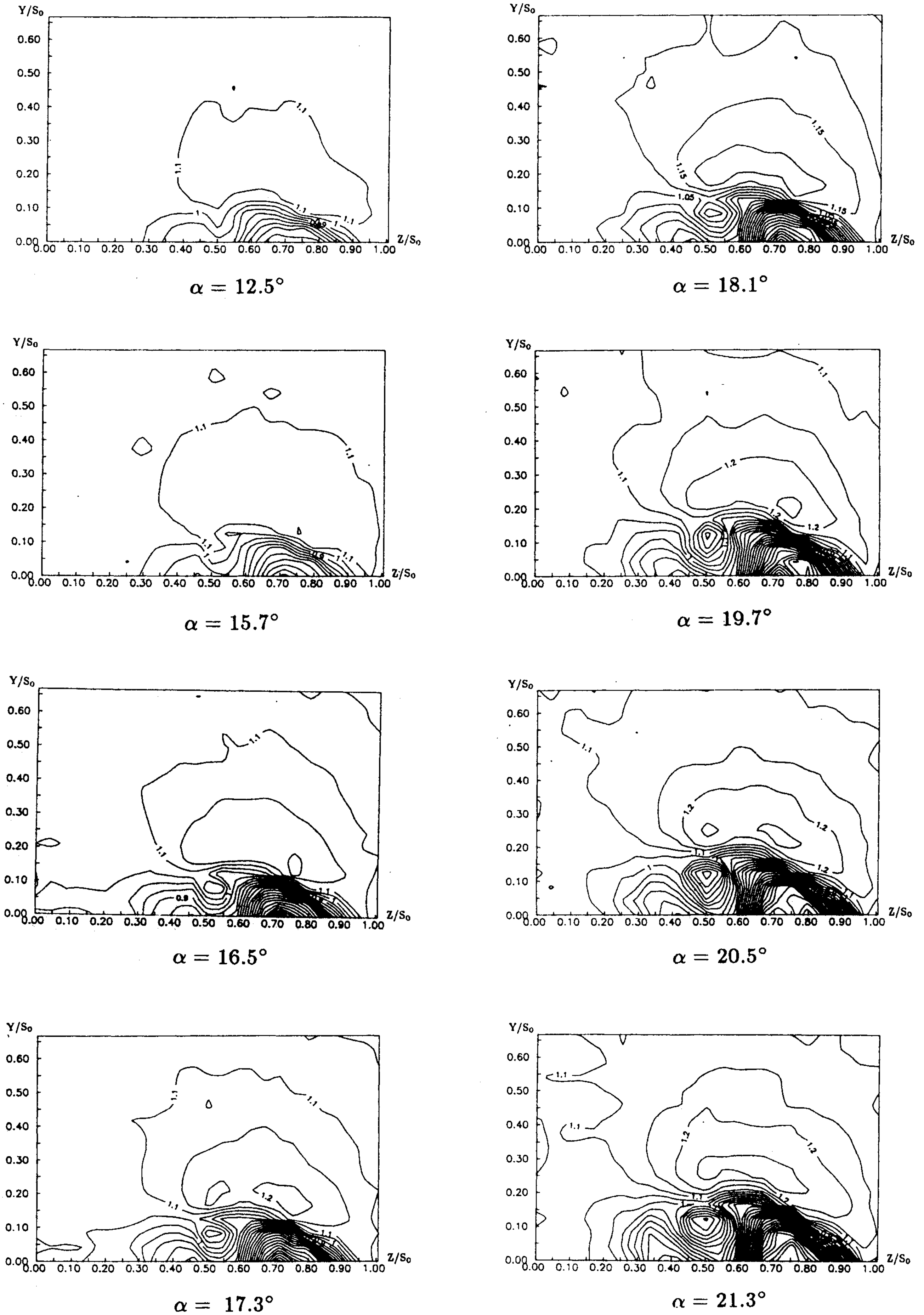


Fig. 10 **Evolution of the U/U_∞ contour maps over the measured cross-sectional plane for 59-deg-sweep delta wing in the ramp pitching-up motion, $K = 0.04$, $Re = 9000$, the pitching center at 1/2 chord length from the trailing edge.**

flowfield is not a straightforward task. Normally, a phase-averaging technique[18] can be used to obtain the ensemble-averaged velocity variations at each measured point, then the spatial flow distribution over a cross section can be constructed through collecting the data on the measured points at the same phase. However, in this study it was realized that such an experimental procedure takes a formidable length of time to perform LDA measurements over a cross-sectional plane for more than 300 grid points. Our experience indicates that a cycle of pitching motion takes more than 1 min for flow returning to its initial state. Alternately, we decided to adopt a low-pass filtering technique[19] to process the velocity signal obtained in a cycle of pitching motion. The filtered velocity data at the measured points are then taken to emulate those resulting from the phase-averaging process. Since the filtered LDA signals obtained at the same point in different cycles of pitching motion appear to be well repeatable as long as the breakdown flow is situated downstream of the cross-sectional plane measured, this technique works satisfactorily as far as the purpose of this work is concerned. The LDA measurements were employed for the 59-deg-sweep and 70-deg-sweep delta wing models. Ramp pitching-up motion was performed with the pitching center at $1/2C$. For the former wing model, K values studied are in a range of $0 \leq K \leq 0.04$. For the latter wing model, the K values chosen are 0.03 and 0.063. In the following, our attention will be focused on the presentation of the data obtained for the 59-deg-sweep delta wing at $K = 0.04$, since for this case the second delay phenomenon is very pronounced as indicated by the previous visualization results.

For the 59-deg-sweep delta wing, $K = 0.04$, $Re = 9000$, and α increasing from 12.5 to 28.5 deg, the evolution of the U velocity distribution over the cross-sectional plane measured is shown in Fig. 10. U denotes the streamwise velocity obtained from the filtered LDA data, where the cutoff frequency of the low-pass filtering process is 1.5 Hz. The most interesting feature found in this figure is on the development of the primary vortex and the secondary separation region. When α is between 12.5 deg and 16 deg, the primary vortex is too small to

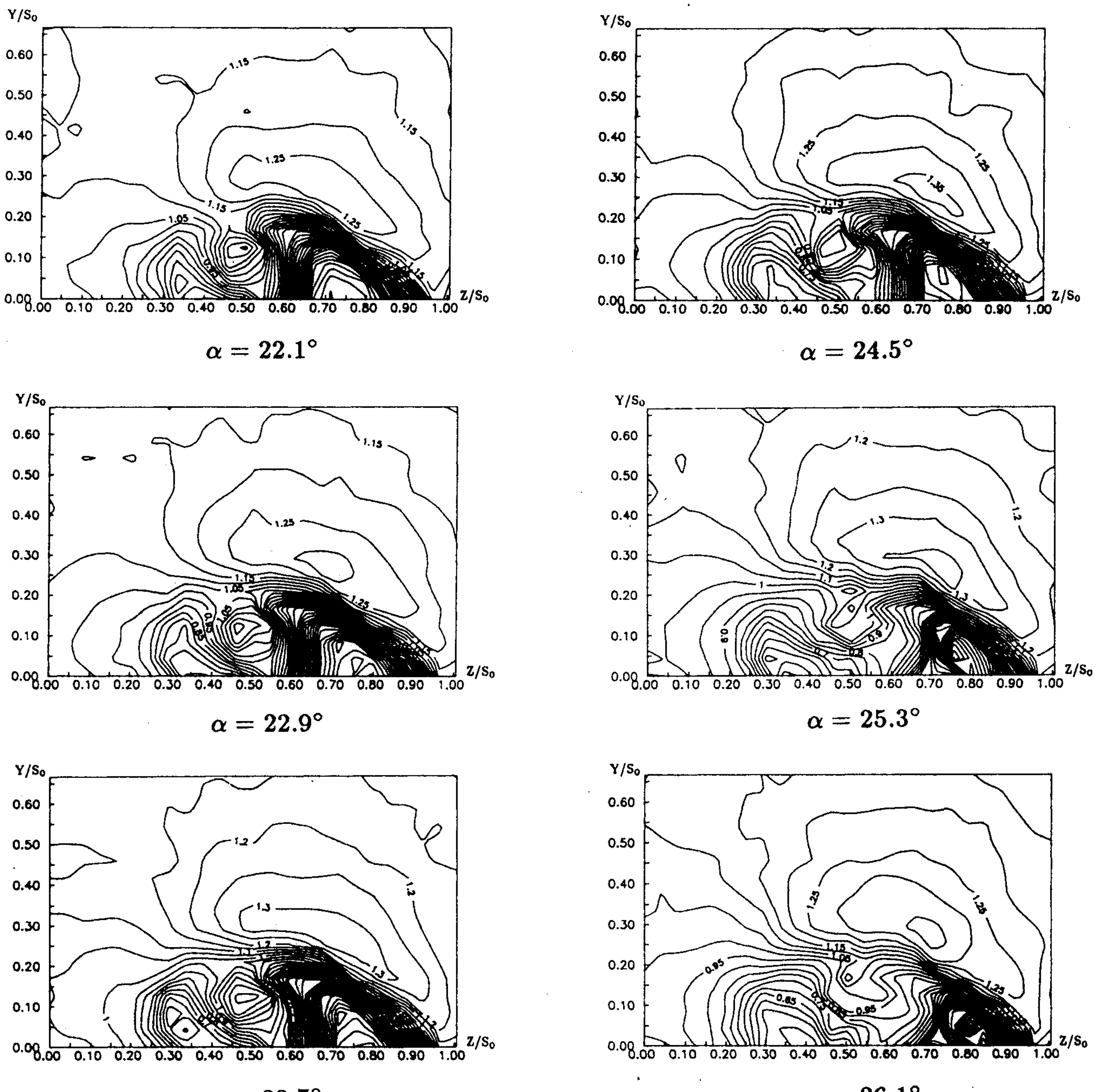


Fig. 10 (continued) Evolution of the U/U_∞ contour maps over the measured cross-sectional plane for 59-deg-sweep delta wing in the ramp pitching-up motion, $K = 0.04$, $Re = 9000$, the pitching center at 1/2 chord length from the trailing edge.

be discerned. When $\alpha = 16.5$ deg, the vortex core is identifiable near the position of $Z/S_0 = 0.53$ and $Y/S_0 = 0.09$ where the value of U measured appears to be the maximum. Referring to the data obtained for the same wing model under the stationary condition shown in Fig. 11a, at $\alpha = 16$ deg a well-defined primary vortex core is situated near $Z/S_0 = 0.5$ and $Y/S_0 = 0.13$; moreover, the primary vortex and the secondary separation region are of sizes larger than those seen in the case of pitching motion (Fig. 10). Evidently, in the pitching-up motion the development of the primary vortex and the secondary separation region lag behind those observed in the stationary situation. As α is between 16.5 deg and 19.7 deg, Fig. 10 indicates that the size of the primary vortex grows to a scale similar to that seen in Fig. 11 at $\alpha = 16$ deg.

In Fig. 11b, it is noted that at $\alpha = 18$ deg the secondary separation region on the stationary wing is reduced in size due to the growth of the primary vortex. However, in Fig. 10 a competition between the development of the primary vortex

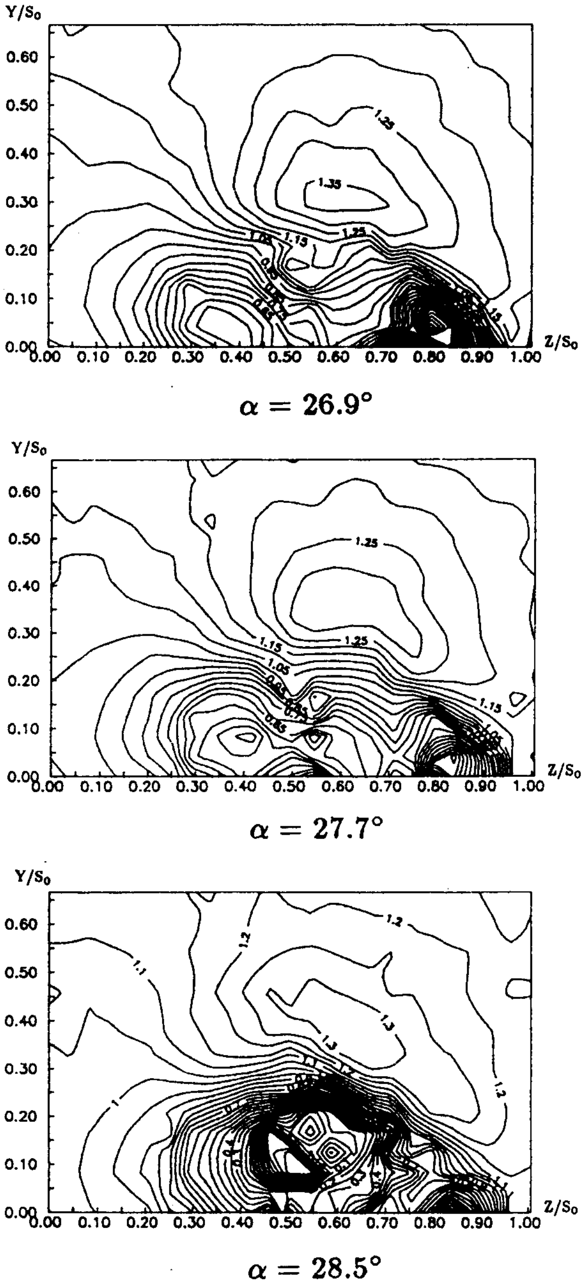


Fig. 10 (continued) Evolution of the U/U_∞ contour maps over the measured cross-sectional plane for 59-deg-sweep delta wing in the ramp pitching-up motion, $K = 0.04$, $Re = 9000$, the pitching center at 1/2 chord length from the trailing edge.

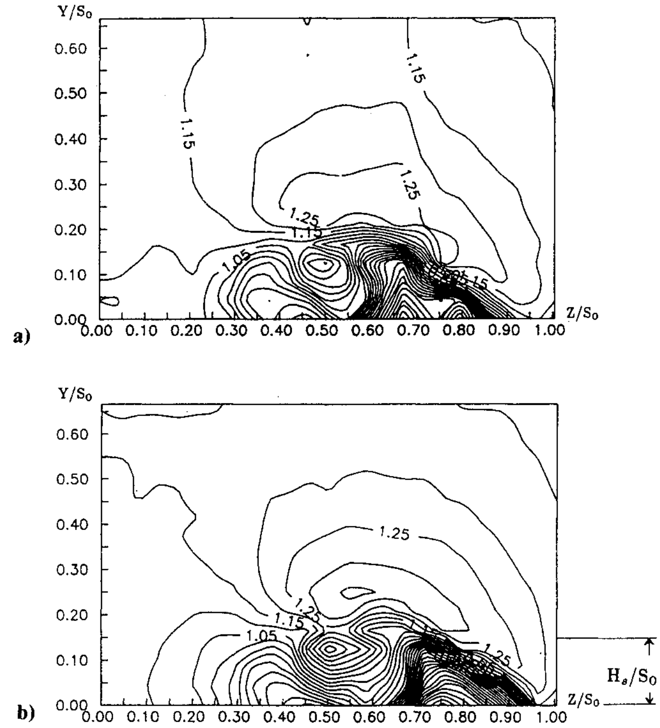


Fig. 11 Streamwise velocity contour maps, U/U_∞ over the measured cross-sectional plane for 59-deg-sweep delta wing, $K = 0$ at $Re = 9000$; a) at $\alpha = 16$ deg; and b) at $\alpha = 18$ deg.

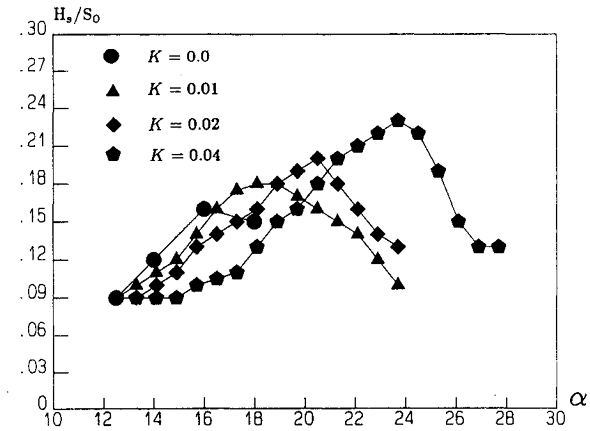


Fig. 12 Development of the secondary separation region on the plane measured vs the α and K for 59-deg-sweep delta wing in the ramp pitching-up motion, the pitch center at 1/2 chord length from the trailing edge, $Re = 9000$.

and the secondary separation region is noticed when α is increasing from 20.5 to 24.5 deg, i.e., during the occurrence of the second delay. Interestingly, it is found that the secondary separation region does not reduce its size, but on the contrary enlarges. Comparing with the results of the stationary case (see Fig. 11), one finds that the development of the secondary separation region during the occurrence of second delay is very interesting. To be more specific, as seen in Fig. 10, when α is between 20.5 deg and 21.3 deg, the primary vortex core is near $Z/S_0 = 0.5$ and $Y/S_0 = 0.13$. When $\alpha = 22.9$ deg, due to the growth of the secondary separation region the core of the primary vortex is apparently displaced inboard, situated at $Z/S_0 = 0.45$ and $Y/S_0 = 0.1$. The growth of the secondary separation region continues until the end of the second delay, namely, near $\alpha = 24.5$ deg. At $\alpha = 25.3$ deg, a dramatic change is noted in the region around $Z/S_0 = 0.5$ and $Y/S_0 = 0.15$, where the primary vortex core appears to be of a larger size which seems to have experienced a process of abrupt diffusion. Meanwhile, the size of the secondary separation region is reduced considerably. As noted, this flow development is associated with the three-dimensional distortion of the primary vortex core near and after the end of the second delay, shown by flow visualization in the foregoing section. At $\alpha = 27.7$ deg, the secondary separation region is reduced to a minimum size and the vortex breakdown point is about passing through this measured plane. Although the ramp pitching motion is stopped at $\alpha = 28.5$ deg, the development of a wake-type flow characteristic continues in the measured cross-sectional plane after the termination of the pitching motion.

Summarizing the results shown in Fig. 10 indicates that the development of the secondary separation region above the delta wings is featured by two distinct characteristics. One is due to underdevelopment of the secondary separation region immediately after the initiation of the pitching motion. The other is that during the occurrence of the second delay the secondary separation region grows to a size which is larger than that found in the stationary case. These two characteristics can be further illustrated quantitatively as shown in Fig.

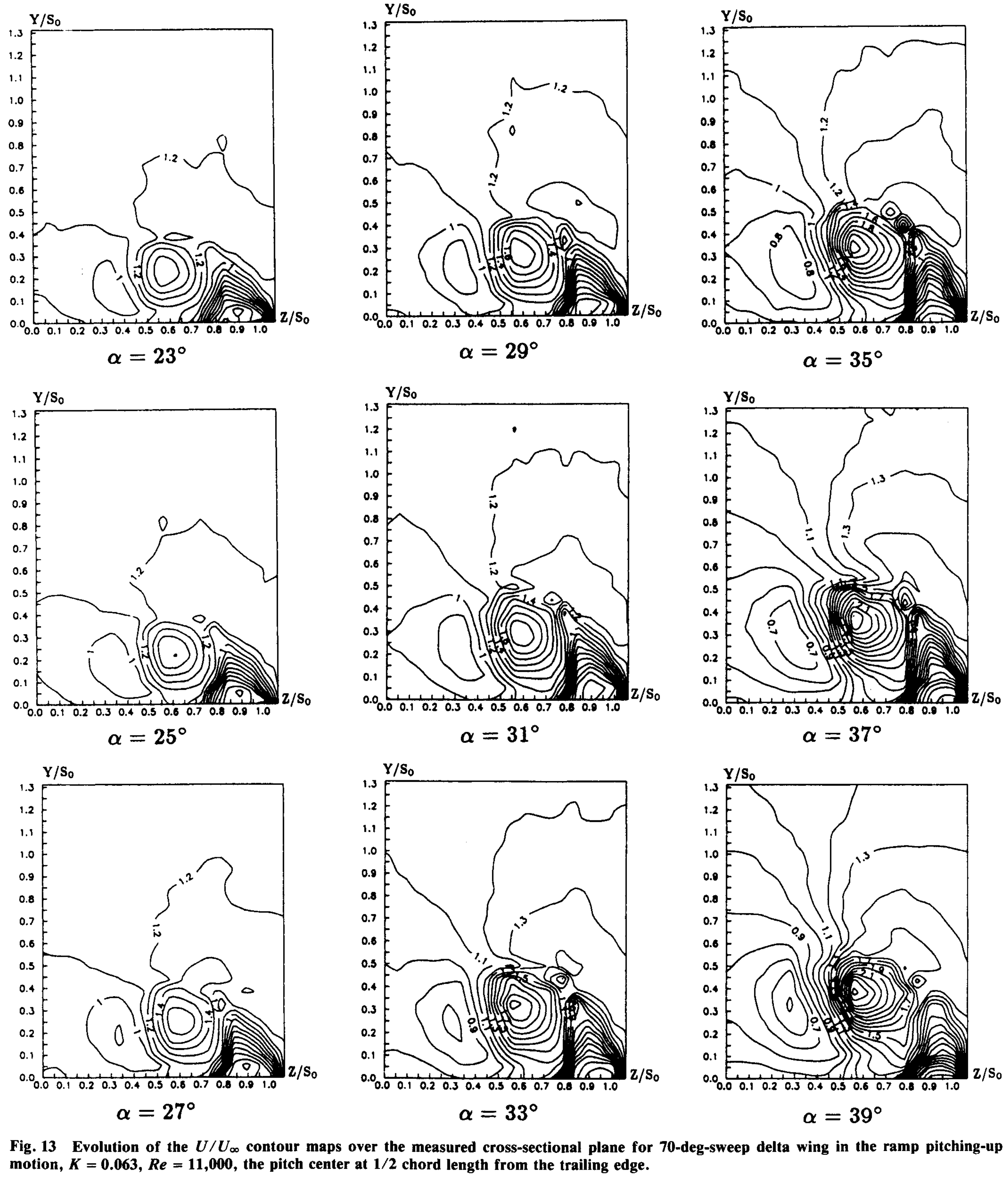


Fig. 13 Evolution of the U/U_∞ contour maps over the measured cross-sectional plane for 70-deg-sweep delta wing in the ramp pitching-up motion, $K = 0.063$, $Re = 11{,}000$, the pitch center at 1/2 chord length from the trailing edge.

12. This figure presents a plot of H_s vs α and K, where H_s denotes the vertical height of the secondary separation region; see Fig. 11b. It is indicated that the higher the K value, the further delay the initial growth of H_s is and the higher the maximum value of H_s at higher α is found.

For the case of the 70-deg-sweep delta wing, the overshoot corresponding to the growth of the secondary separation region is also observed. However, this growth of the secondary separation region does not deter the development of the primary vortex during the pitching-up motion. In the meanwhile, as noted previously, no occurrence of second delay on this wing model is found. The streamwise velocity contour maps of the 70-deg-sweep delta wing undergoing pitching-up motion from $\alpha = 21$ deg to 41 deg at $K = 0.063$ are shown in Fig. 13 for comparison. An interesting finding noted in this figure is that the primary vortex moves outward as α increases. This implies that the primary vortex and secondary separation region can grow simultaneously as α increases.

Discussion

According to the earlier observations,[19] for a stationary delta wing the phenomenon of vortex breakdown is featured by the observation that the vortex is developed into a sufficiently large size and its circulation reaches a critical value. Based on this finding, the occurrence of the first delay of vortex breakdown in a ramp pitching-up motion is suggested due to the underdevelopment of the primary vortex. This situation is evidenced in Fig. 10 as α is increasing from 12.5 to 18.1 deg. Similar argument can also be applied to the occurrence of the second delay although this phenomenon is realized to be much more complicated than the phenomenon of first delay. In Fig. 10, when α is increasing from 20.5 to 24.5 deg, the underdevelopment of the primary vortex is also observed, which as mentioned is due to the growth of the secondary separation region.

The underdevelopment of vortical flow in a pitching-up motion was noted by Gad-el-Hak and Ho.[5] In their study, a 45-deg-sweep delta wing performed a sinusoidal pitching motion. The pitch center is located at 0.25 root chord length from the wing apex, and a laser-sheet light plane is employed to illuminate the cross-sectional plane at 0.8 root chord length from the wing apex. They showed that during the pitching-up motion the vortex is smaller in size than that seen in the stationary case. These observations are consistent with the present finding, although the delta wing models employed in the two studies are different.

Several features concerning the phenomenon of second delay of vortex breakdown propagation which have been described in the foregoing sections deserve further discussion here. The first is on the occurrence of second delay depending on the sweep angle of the delta wing model. Flow-visualization results indicate that the significance of this delay gets less pronounced as the sweep angle increases. According to the LDA data obtained, a physical reason supporting this trend is that the suppression of the primary vortex due to the growth of the secondary separation region gets less significant as the sweep angle increases. The second is this phenomenon depending on the initial angle of attack of pitching-up motion. For instance, for the 59-deg sweep delta wing, it was noted that if the initial α is equal or larger than 18 deg the occurrence of second delay can be suppressed. A tentative explanation is that if the initial α is 18 deg or higher, the primary vortex of the 59-deg-sweep delta wing is of a size so large that during the pitching-up motion the suppression of the primary vortex by the growth of the secondary separation region can be ineffective. Hence, the phenomenon of second delay of vortex breakdown does not appear. The third is on the angles of attack corresponding to the occurrence of second delay depending on the reduced pitching rate K (see Fig. 3a). It is shown by flow-visualization and LDA data obtained that the values of α corresponding to the second delay get higher as the value of K increases. Further found is that as K increases the secondary separation region can grow to a larger size at higher α, while the second delay of vortex breakdown is ended about when the secondary separation region is starting to reduce its size.

Conclusion

1) Two occurrences of delay concerning the propagation of the vortex breakdown point on a pitching delta wing are observed. The first delay is found for all delta wing models studied, 70 deg $\geq \Lambda \geq$ 59 deg, regardless of pitching-up or pitching-down motion. The time length associated with this delay is comparable to C/U_∞, and is insensitive to the initial position of the breakdown point. The occurrence of the second delay is observed in the process of the delta wing undergoing pitching-up motion. This phenomenon strongly depends on the sweep angle of the delta wing and the rate of pitching motion. The second-delay phenomenon gets pronounced as the sweep angle of the delta wing decreases and K increases.

2) Except for the durations while the delay phenomena occur, the propagation speed of the breakdown point can be estimated by an expression of $2r^*KU_\infty$, where r^* is the slope of the vortex breakdown positions vs α for the stationary wing.

3) As the wing model undergoes pitching-up motion, the results of LDA measurement suggest that the delay occurrences of vortex breakdown propagation are due to the underdevelopment of the primary vortex. As shown by the data of the 59-deg-sweep delta wing at $K = 0.04$, during the occurrence of the second delay the secondary separation region grows to a size larger than that found in the stationary case, which consequently suppresses the development of the primary vortex. For the 70-deg-sweep delta wing in a pitching-up motion, the secondary separation region also grows to a size larger than that found in the stationary case. However, this growth does not suppress the development of the primary vortex.

References

[1]Herbest, W. B., "Dynamics of Air Combat," *Journal of Aircraft*, Vol. 20, No. 7, 1983, pp. 594–598.

[2]Skow, A. M., and Erickson, G. E., "Modern Fighter Aircraft Design for High-Angle-of-Attack Maneuvering," AGARD-LS-121, Paper 4, March 1982.

[3]Kegelman, J. T., and Roos, F. W., "Effect of Leading-Edge Shape and Vortex Burst on the Flowfield of a 70 Degree Sweep Delta Wing," AIAA Paper 89-0086, Jan. 1989.

[4]Vigevano, L., "Strake-Wing-Body Combinations," AGARD-LS-121, Paper 13, March 1982.

[5]Gad-el-Hak, M., and Ho, C. M., "The Pitching Delta Wing," *AIAA Journal*, Vol. 23, No. 11, 1985, pp. 1660–1665.

[6]Gad-el-Hak, M., and Ho, C. M., "Unsteady Vortical Flow Around Three Dimensional Lifting Surface," *AIAA Journal*, Vol. 24, No. 5, 1986, pp. 713–721.

[7]LeMay, S. P., Batill, S. M., and Nelson, R. C., "Vortex Dynamics on a Pitching Delta Wing," *Journal of Aircraft*, Vol. 27, No. 2, 1990, pp. 131–138.

[8]Soltani, M. R., and Bragg, M. B., "Experimental Measurements on an Oscillatory 70 Degree Delta Wing in Subsonic Flow," AIAA Paper 88-2376, June 1988.

[9]Jarrah, M. A., "Low-Speed Wind Tunnel Investigation of Flow About Delta Wings Oscillating in Pitch to Very High Angle of Attack," AIAA Paper 89-0295, Jan. 1989.

[10]Atta, R., and Rockwell, D., "Leading Edge Vortices Due to Low Reynolds Number Flow past a Pitching Delta Wing," *AIAA Journal*, Vol. 28, No. 6, 1990, pp. 995–1004.

[11]Magness, C., Robinson, O., and Rockwell, D., "Control of Leading-Edges Vortices on a Delta Wing," AIAA Paper 89-0999, March 1989.

[12]Thompson, S., Batill, S., and Nelson, R., "The Separated Flow Field on a Slender Delta Wing Undergoing Transient Pitching Motions," AIAA Paper 89-0194, Jan. 1989.

[13]Reynolds, G., and Abtahi, A., "Three-Dimensional Vortex Development, Breakdown and Control," AIAA Paper 89-0998, March

1989.

[14]Wentz, W. H., and Kohliman, D. L., "Vortex Breakdown on Slender Sharp-Edges Wings," *Journal of Aircraft*, Vol. 8, No. 3., 1971, pp. 156-161.

[15]Lee, M., Shih, C., and Ho, C. M., "Response of a Delta Wing in Steady and Unsteady Flow," ASME Applied Mechanics, Bioengineering and Fluids Engineering Conference, Cincinnati, OH, June 1987.

[16]Gad-el-Hak, M., and Blackwelder, R. F., "The Discrete Vortices from a Delta Wing," *AIAA Journal*, Vol. 23, No. 6, 1985, pp. 961, 962.

[17]Payne, F. M., Ng, T. T., and Nelson, R. C., "Visualization and Wake Surveys of Vortical Flow over a Delta Wing," *AIAA Journal*, Vol. 26, No. 2, 1988, pp. 137-143.

[18]Miau, J. J., Lee, K. C., Chen, M. M., and Chou, J. H., "Control of Separated Flow by a Two-Dimensional Oscillating Fence," *AIAA Journal*, Vol. 29, No. 7, 1991, pp. 1140-1148.

[19]Chang, R. C., "Studies of Vortical Flow Developed on Stationary and Pitching Delta Wings," Ph.D. Thesis in preparation, Inst. of Aeronautics and Astronautics, National Cheng-Kung Univ., Taiwan, ROC, 1991.