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Experimental Study of Vortex Flows over Delta Wings in Wing-Rock Motion

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The phenomenon of wing rock was investigated using flow visualization in a water tunnel. Models with 70-deg, 75-deg, 80-deg, and 85-deg sweeps were tested in a free-to-roll rig and a forced oscillation rig. Wing rock was observed to occur on various wings in the absence of asymmetric vortex liftoff, vortex breakdown, and static hysteresis. These phenomena are therefore not the necessary ingredients for wing rock. The presence of these phenomena, however, can have strong influence on characteristics such as the amplitude and frequency of wing rock.

Nomenclature

b = wing span
k = reduced frequency, $\omega b/V$
L = left side (from a hypothetical pilot's viewpoint)
R = right side (from a hypothetical pilot's viewpoint)
V = freestream velocity
α = nominal angle-of-attack
β = sideslip angle
$\Delta\phi$ = roll or wing rock amplitude (half of peak-to-peak value)
θ = apex angle
ϕ = roll angle
ω = angular velocity

I. Introduction

MODERN fighter aircraft are operating in a flight regime that requires maximum maneuverability and controllability in order to be effective in the combat arena. One of the limitations[1] to combat effectiveness for all fighter aircraft is the phenomenon of wing rock, a moderate to high-angle-of-attack dynamic motion manifested primarily in a limit-cycle oscillation in roll with, in some cases, a coupled oscillation in yaw. Wing rock can occur at moderate angles of attack in the transonic Mach number region as a result of shock-wave/boundary-layer interactions on the wing, or it can occur at airspeeds below the corner speed on the aircraft at angles of attack in the vicinity of stall. Generally, the onset of wing rock is attributed to a loss of stability in the lateral/directional mode and can be caused by a number of different aerodynamic phenomena. The present study addresses wing rock in the subsonic, high-angle-of-attack regime.

Attempts have been made in recent years on specific aircraft configurations[2,3] using a variety of both controls-oriented and aerodynamic fixes to cure wing-rock problems. There is, however, a lack of information that provides consistent and well-documented solutions to wing rock in general. The specific aerodynamic causes of wing rock are undoubtedly configuration-dependent, but there may very well be some phenomena common to all aircraft. The search for an explanation of the aerodynamic causes for the wing-rock motion has led researchers to suggest and investigate a variety of aerodynamic characteristics including:

1) Nonlinearities of static lateral and directional coefficients (primarily rolling and yawing moments) with sideslip or roll angle
2) Static hysteresis of the rolling moment with roll or sideslip angles
3) Dependence of roll damping on sideslip angle such that negative damping is obtained at the smaller sideslip angles and positive damping is obtained at larger angles
4) Nonlinear variation of roll damping with roll rate (frequency of oscillation) and amplitude of oscillation

A number of aerodynamic phenomena have been suggested as direct causes of the aerodynamic instability contributing to wing rock including: 1) zero sideslip vortex asymmetric liftoff from the wings or forebody; 2) asymmetric vortex breakdown over the wings with variation in sideslip angle or roll angle; 3) static hysteresis associated with vortex breakdown and vortex liftoff; and 4) time or phase lag effects of vortex lift with respect to vehicle motion as reflected in roll damping.

Research efforts have been ongoing in order to understand the complexities of high-angle-of-attack vortex flows, in general. Some examples of relatively recent studies aimed at understanding flows pertinent to wing rock are shown in Refs. 4–18.

Some recent assessment (e.g., Refs. 11 and 12) of the fundamental mechanisms producing the wing rock motion concluded that one primary flow mechanism causing the wing rock was the variation in position of the two vortices under dynamic conditions. Specifically, the displacement of the leeward vortex from the surface of the upgoing side of the wing is seen as the primary mechanism that provides the static restoring moment reflected in the lateral stability coefficient, $C_{l\phi}$, and the variation in roll damping with sideslip, β, which causes the limit-cycle wing rock. It was concluded[11] from these tests that the wing-rock amplitude is directly related to the variation of roll damping with sideslip, while the wing-rock period is determined only by the level of static lateral stability.

Experiments specifically addressing wing rock were reported in Ref. 10 and included static force tests, forced oscillation, free-to-roll and rotary-balance tests. The 80-deg, sharp edged model was tested on the free-to-roll rig at angles of attack to 42 deg. It was found that for $\alpha < 25$ deg, the wing did not experience wing rock, while at $\alpha > 25$ deg, the wing showed oscillation amplitudes in roll up to ± 40 deg. Unstable roll damping was found to exist at angles of attack above $\alpha = 20$ deg, while the free-to-roll test indicated wing rock does not start until $\alpha = 27$ deg. The explanation given for this discrepancy is that there is friction in the free-to-roll

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apparatus and that the initial forces to induce wing rock are too small at $\alpha = 20$ deg to overcome it. The initiation of the wing rock motion is delayed to a higher angle of attack where the magnitude of the force is higher.

Free-to-roll tests performed in Ref. 11 used 76-deg and 80-deg delta wings. The 76-deg wing showed no evidence of wing rock. The 80-deg wing experienced self-induced wing rock beginning at $\alpha = 20$ deg, which is closer to the angle of attack for wing rock initiation that would be expected from the roll damping data of Ref. 10. The maximum roll oscillation amplitude occurs at $\alpha = 25$ deg for Ref. 11 and $\alpha = 35$ deg for Ref. 10. The initiation of wing rock for the two experiments is also different; $\alpha = 20$ deg for Ref. 11 and $\alpha = 27$ deg, for Ref. 10. The differences in the two experiments are significant and have not been fully explained as yet. The difference between the two wing rock experimental results may be partially due to less friction in the rig of Ref. 11 compared to that of Ref. 10 and, perhaps more importantly, the differences in model configurations. One potentially significant difference between the two experiments is the placement of the models on their respective roll rigs. In Ref. 10, the model axis is offset from the rig roll axis, whereas in Ref. 11, the model and rig axes are coincident.

The primary objectives of this study are to investigate the phenomenon of wing rock on wings with different sweeps and to assess some of the suggested causes of wing rock. Most of the previous experiments on wing rock were performed with 80-deg wings. There is perhaps an implicit suggestion that the vortex flow behaviors over a sharp edge wing during wing rock are relatively insensitive to the wing sweep. Water tunnel experiments with a free-to-roll rig and a forced-oscillation-in-roll rig were carried out. General characteristics of wing rock for different wing planforms were studied.

II. Experimental Approach

The experiment was conducted in the Eidetics International Visual Aerodynamics Division 1520 Flow Visualization Water Tunnel. The facility is a continuous horizontal flow tunnel with a test section 20 in. high × 15 in. wide × 60 in. long. The test section is a channel constructed of tempered glass which allows both side and planform views. In addition, a downstream transverse window provides an upstream end view without any flow obstruction. The tunnel speed can be varied from 0 to 1 ft/s.

The model was attached to a $\frac{3}{8}$-in.-diam brass sting. Two rolling rigs were used for the experiment: a free-to-roll (FTR) rig and a forced-oscillation-in-roll (FO) rig. In both rigs the model was mounted in an inverted position. In the FTR rig the model sting was fitted through a bearing located in the sting support. This setup allowed a single degree of freedom rolling motion. The model was statically balanced so that its center of gravity aligned closely with the roll-axis. The sting support was attached to a metal frame which allowed angle of attack (α) adjustment.

Tests were conducted on four sharp-leading-edge delta wing models with sweep angles of 70 deg, 75 deg, 80 deg, and 85 deg. Each of the models was 10 in. in length. The sharp-leading-edge models were made of $\frac{1}{8}$-in. aluminum and had a 25-deg single bevel cut from the leading edge. The models were painted glossy white to provide a neutral background for the color dye. The free-to-roll tests were conducted at a free-stream tunnel speed of 10 in./s (Reynolds number = 28,000 based on the wing chord), while the static and forced oscillation tests were conducted at a tunnel speed of 3 in./s (Reynolds number = 8,300).

Most of the tests were conducted with two 0.040-in.-diam dye tubes taped along the midspan of the model on the windward side with the tube outlets located near the apex of the model. Tests were also done with dye tubes on the leeward side for comparison. Unless specified otherwise, the results to be presented are with the dye tubes on the windward side. Some tests were repeated with the model being rotated 180 deg about the roll axis to make sure that the effect due to possible small misalignment of the center of gravity or model asymmetrics was minimal. Video recordings and still photos of the side and planform views were made of the model motion and flow field. The primary interest was in the behavior of the vortex flows created from the leading edges. Specifically, wing rock frequencies and amplitudes, vortex trajectories, and vortex bursting locations were of prime interest. The emphasis was on correlating the vortex behavior with the model motion. Differences among the various model configurations were noted and analyzed.

III. Results

For a delta wing with one degree of freedom in roll through an angle ϕ, changes in the effective apex angle and angle-of-attack are induced. For a positive roll angle (rolling right), the right (windwind) half of the wing will experience an effective increase in the apex angle (or decrease in sweep angle), while the left (leeward) half will experience a reduction in the apex angle, and vice versa. The effective angle of attack, however, always decreases with roll angle, regardless of the sign of rotation.

Generally, wing rock refers to a steady, near-sinusoidal roll motion about the model center axis. During the course of this study, other forms of "rocking" motion which are more irregular in behavior were also observed. For discussions below, the former will be referred to as "regular" wing rock while the latter as "irregular" wing rock motions.

A. Free-to-Roll Results

Wing rock was observed for all the sharp-edge wings tested except the 70-deg wing. At the angles of attack where wing rock initially occurs, an initial roll input was usually needed in order to overcome the bearing friction. At higher angles of attack the rocking motion was self-induced. Wing rock amplitudes of the 75-, 80-, and 85-degree, sharp-edge wings as a function of the angle of attack are shown in Fig. 1. As expected, increasing the sweep angle leads to the onset of wing rock at lower angles of attack. Overall, the wing rock amplitude of 80-deg wing is higher than the 85-deg and 75-deg wings.

1. 80-Deg Wing

Wing-rock of the 80-deg wing starts at an α of about 25 deg. Vortex breakdown stays beyond the trailing edge at $\alpha = 25$ deg and propagates upstream towards the apex as α increases. The wing rock of this model is characterized by the alternate lift-off and reattachment of the leading edge vortices, which, as explained by Ericsson,[12] produce an undamped rolling movement and the positive aerodynamic spring needed for the oscillation in roll. The flow visualization in Fig. 2 shows one complete cycle of wing rock at $\alpha = 40$ deg. A dynamic hysteresis was revealed by the dependence of vortex trajectories on the direction of motion at a given roll angle. A phase shift between the model motion and the vortex response is also evident with the total detachment of the vortex occurs at near the zero rather than the maximum roll angle. Note also that the vortex detachment/attachment does not occur simultaneously along the entire vortex; rather, it starts at the apex and propagates to the rest of the vortex as the wing motion continues.

Regular wing rock motion persists until the α reaches 55 deg. At $\alpha = 55$ deg, vortex breakdown occurs very close to the apex for both vortices with one side breaks down farther forward of the trailing edge than the other. At this condition the vortex lift is small. Thus the large amplitude wing-rock motion caused by vortex asymmetry ceases and only small, erratic motions due to the breakdown unsteadiness were observed.

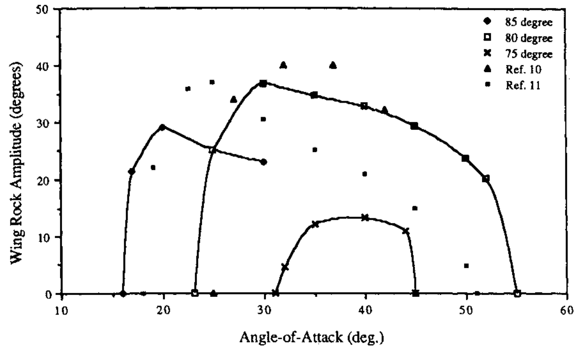

Fig. 1 Wing rock amplitude vs angle of attack for wings with different sweeps.

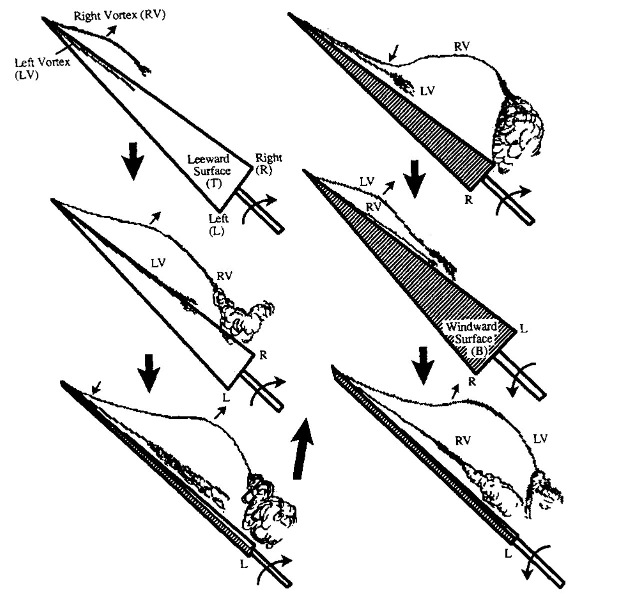

Fig. 2 Vortex motion during wing rock of the 80-deg wing at 40-deg angle of attack.

Hence for the 80-deg, sharp leading edge wing the wing rock motion and the vortex flow observed are consistent with results from many previous studies. Asymmetric vortex liftoff is shown to be a feature of wing rock, and vortex breakdown is a mechanism that limits the amplitude of wing rock. The location of the dye tubes does not have a noticeable effect on the vortex flow.

2. 85-Deg Wing

Unlike the 80-deg wing, the location of the dye tubes on the 85-deg wing has a strong effect on the vortex flow during wing rock. With the dye tubes on the windward side, wing rock for the 85-deg wing starts at an α of 17 deg. The wing rock on this model is characterized initially by the alternative liftoff and reattachment of the leading edge vortices. Vortex breakdown occurs over the wing on the attached vortex at $\alpha = 17$ deg and propagates upstream towards the apex as the α increases. A motion dependence of the vortex trajectory and a phase shift in vortex response again can be observed. As the α increases to 25 deg, however, one of the vortices stays attached to the surface without bursting throughout the wing rock cycle, while the other vortex goes through the liftoff and reattachment process. That is, the wing rocks between two positions where the vortices are attached on both sides or lift off asymmetrically. The observed wing rock motion remains reasonably regular.

At $\alpha = 35$ deg, the regular wing rock is replaced by erratic rolling motions. A sequence of the motion is shown in Fig. 3. At the maximum negative roll angle, both vortices begin to lift off from the surface, and the wing starts to roll in the positive direction. Liftoff of the vortices continue until the wing reaches a small positive roll angle. At this angle both vortices begin to reattach and the wing motion ceases momentarily. The reattachment process continues with the wing fixed in this roll angle until at a certain time later the wing starts to roll in the negative direction. This causes the vortices to lift off again and complete one sequence of the motion. This sequence of motion does not occur at a regular interval, but the motion is similar whenever it occurs.

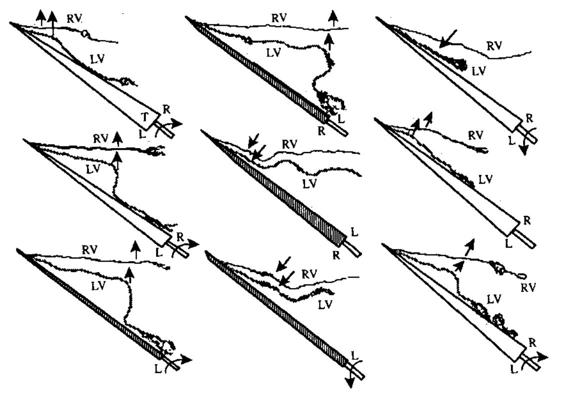

Fig. 3 Vortex motion during wing rock of the 85-deg wing at 35-deg angle of attack.

Thus instead of the alternative liftoff and reattachment of the right and the left vortices, the wing rocks between two positions at which the vortices are either both attached or both detached. At the maximum negative roll angle, with both vortices detached, the positive rolling moment is provided by aerodynamic forces other than vortex lift. When the vortices become reattached at a certain positive roll angle, the asymmetric vortex pattern induces a negative roll moment which eventually causes the wing to rock back. This irregular "rocking" motion persists to higher α's.

Thus for the 85-deg wing, wing rock is no longer just characterized by alternative vortex liftoff. Various combinations of vortex asymmetries can lead to wing rock motion. The vortex flow is also substantially altered when the dye tube are placed on the leeward surface of the 85-deg wing. The flow during wing rock is now characterized by the alternate liftoff of the left and right vortices through the range of angle of attack. Thus on highly slender wings small geometric differences can lead to significant differences in the wing rock characteristics and vortex behaviors.

3. 75-Deg Wing

Contrary to Levin and Katz[11] who observed no wing rock for a 76-deg wing, wing rock was observed for the 75-deg wing. It is unlikely that the 1 deg decrease in sweep angle is sufficient to account for the difference. Rather, the difference was seen to be a result of the bearing friction in their apparatus and/or the large centerbody of their model.

Wing rock for this wing starts at $\alpha = 31$ deg. At this α, no vortex breakdown forward of the trailing edge was observed. Furthermore, no asymmetric vortex lift-off can be observed either. A small difference in the left and right vortex positions at a given roll angle exists, depending upon the direction of motion.

At $\alpha = 35$ deg, shown in Fig. 4, vortex breakdown occurs on only one side of the wing. As demonstrated in Fig. 4, depending on the initial flow condition, the breakdown can occur on either side of the wing but will not switch sides during rocking. No sudden vortex liftoff occurs for either vortices. The vortex breakdown location stays approximately constant through the cycle of wing motion instead of moving in response to changes in the effective apex angle.

At $\alpha = 40$ deg, vortex breakdown occurs on both sides of the wing. Again no vortex liftoff occurs, though there are more movements in the breakdown points compared with at

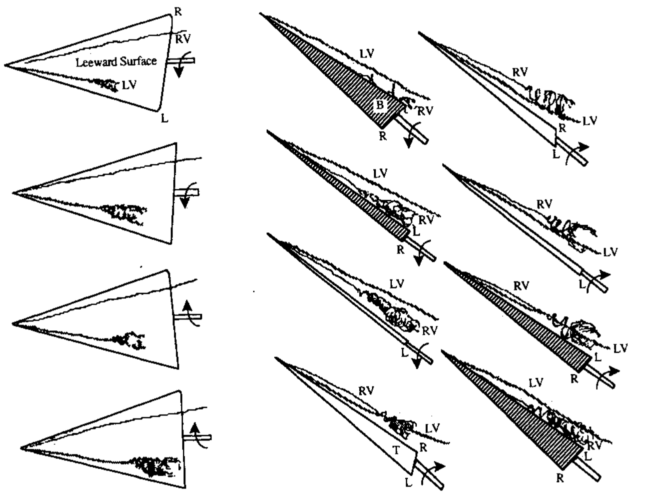

Fig. 4 Vortex motion during wing rock of the 75-deg wing at 35-deg angle of attack: a) Planform view and b) Side view; hysteresis is demonstrated by the switching of the vortex breakdown from the left (Fig. 4a) to the right.

α = 35 deg. The wing rock persists in this manner until α reaches 45 deg, at which the vortex breakdown occurs very close to the apex and the rocking motion is damped.

B. Static and Force Oscillation Results

Results from the forced oscillation rig, the free-to-roll rig, and static tests will be discussed in this section. A sinusoidal oscillation was used for the FO study. Of particular interest are the dynamic responses of vortex breakdown and vortex trajectory. Due to limitations in the forced oscillation rig, exact reduced frequency and amplitude duplications of the corresponding free-to-roll cases can be achieved only for the 80-deg sharp leading-edge wing.

1. *Static Results*

Tests were performed with the wings at fixed α and ϕ to investigate vortex behaviors at static conditions. The two phenomena of interest are vortex liftoff and vortex breakdown. One observation that is common to all the wings tested is that asymmetric vortex liftoff was never observed at zero-roll. That is, the vortex asymmetry which initiates wing rock does not manifest itself in the form of asymmetric vortex liftoff. This is in agreement with wind tunnel results in Ref. 17 but disagrees with some other static results (e.g., see Ref. 12) that suggested asymmetric liftoff for an 80-deg sharp edge wing at α's above 27 deg. The reason(s) for this discrepancy is (are) unknown at this point.

At sufficiently large roll (or sideslip) angles, the leeward-edge vortex begins to lift off (i.e., a relatively large displacement of the vortex from the surface due to a small change in roll angle) from the surface. Also of interest is that a vortex will break down over the wing only if the vortex stays "attached," or in other words, a detached vortex will not break down over the wing. That is, for a given vortex, liftoff and breakdown over the wing seem to be mutually exclusive at static conditions.

Figure 5 shows the vortex breakdown location over the 75-deg and 80-deg wings at various roll angles at a nominal 35 deg angle of attack. At this angle of attack, vortex breakdown for both wings occurs only on one side of the wing. The breakdown will switch from one side to the other at sufficiently large roll angles. For a given wing, increasing the roll angle will advance the vortex breakdown of the windward vortex upstream towards the apex until at larger roll angles where the reverse occurs. This is probably a result of the interference from the flow around the leeward edge and/or a decrease in the effective angle of attack.

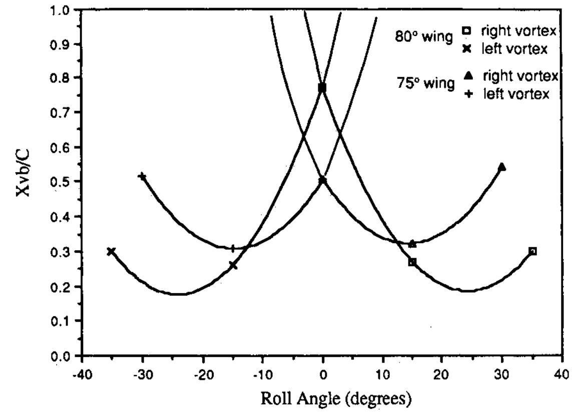

Fig. 5 Vortex breakdown position as a function of roll angle at α = 35 deg for the 80- and 75-deg wings at static condition.

2. *Force Oscillation Results*

Under unsteady conditions, the time-lag effects associated with vortex position and breakdown become important factors. The vortex behavior can be significantly affected by the history of the wing motion. Vortex liftoff, which at static and lower oscillation rates exists only at moderate-to-large roll angles, becomes a prominent feature throughout the oscillation cycle at high oscillation rates. Thus, it would seem that vortex lift-off is mainly a result of the time-lag of vortex position when large roll or sideslip angles are encountered during the oscillation cycle.

Characteristics of the 80-deg wings. Static results for the 80-deg, sharp-edged wing at α = 35 deg show that vortex breakdown occurs on one side of the wing. When the wing is forced to oscillate at a reduced frequency of 0.15 and amplitude of 35 deg, the vortices lift off alternatively as in the free-to-roll situation. When compared with the static results, vortex breakdown is delayed on the attached vortex. Similar trend holds true even when k is increased to 0.25. The vortex breakdown can be seen to have a slower response than the vortex trajectory. When the amplitude of oscillation is increased to 45 deg, vortex breakdown penetrates further forward over the wing. The slow dynamic response of breakdown is further demonstrated by the large phase shift between the breakdown location and the instantaneous wing position, with breakdown occurs farthest forward at a small roll angle. The vortex liftoff process does not occur simultaneously along the entire length of the vortex. That is, the instantaneous position of a vortex during liftoff is a function of the chordwise position.

At higher reduced frequencies, the time-lag effect of vortex liftoff along the chordwise direction becomes strongly evident. Figure 6 compares results of the 80-deg wing at k = 0.25 and 0.66 (the natural wing-rock frequency). As mentioned previously, compared with the static situation, the initial effect of increasing the oscillation rate is to delay vortex breakdown. Figure 6, however, shows that when the oscillation frequency is increased to higher values such as the natural value, breakdown will propagate back onto the wing and towards the apex. The maximum and minimum displacements of a vortex from the wing surface, which signify "complete" liftoff and reattachment respectively, can occur at very different phases of the oscillation cycle depending on the chordwise location. That is, vortex liftoff is not a localized phenomenon. Rather, the liftoff and reattachment processes always start at the apex and propagate downstream. This results in a significant curvature in the vortex trajectory at high oscillation rates. The combined effect of the time-lag associated with breakdown and liftoff can result in the existence of partial liftoff and breakdown on the same vortex, as opposed to the static case where the two events seem to be mutually exclusive.

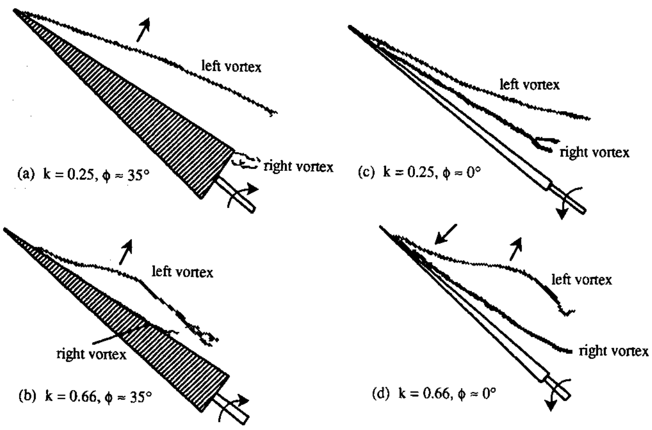

Fig. 6 Effect of oscillation frequency on the vortex flow behaviors over the 80-deg wing at 35-deg angle of attack.

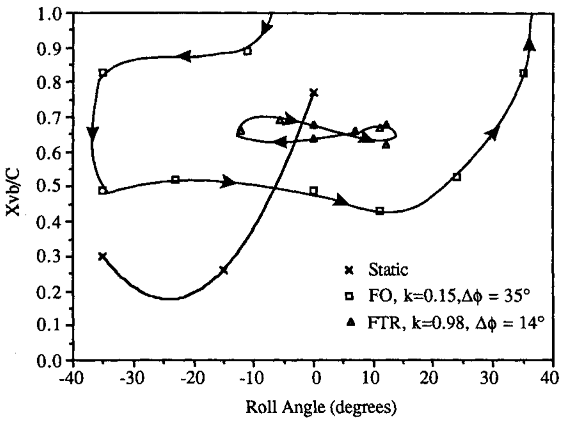

Fig. 7 Left vortex breakdown location for the 75-deg wing at α = 35 deg: free-to-roll, forced oscillation at k = 0.15 and $\Delta\phi$ = 35 deg, and static.

Characteristics of the 85-deg wing. Natural wing rock on this wing is characterized by various forms of vortex asymmetry, depending on the angle of attack. The wing rock motion becomes irregular at moderate-to-high angles of attack. When forced to oscillate in a sinusoidal manner, the vortex flow is characterized by alternate vortex liftoff with associated time-lag effects similar to those of the 80-deg wing. Thus the imposed symmetry from the forced oscillation has a similar effect as placing dye tubes on the leeward surface. That is, the motion of the vortices is "regularized."

Characteristics of the 75-deg wing. Natural wing rock of the 75-deg wing is characterized by attached vortices with and without breakdown. Figure 7 shows the left vortex breakdown location over the wing at static condition, forced oscillation at k = 0.15 and $\Delta\phi$ = 35 deg, and free-to-roll condition at α = 35 deg. For the static condition and forced oscillation, breakdown will switch between the left and right vortices at large roll angles as opposed to the free-to-roll case where the breakdown will occur on only one of the vortices. A comparison between static and forced oscillation results shows that breakdown is delayed due to the wing motion. The forced oscillation result also shows that changes in the breakdown location occur mostly near the extreme roll angles where the wing motion is slow. At higher oscillation frequencies such as in the free-to-roll case (k = 0.98), the breakdown location remains essentially fixed.

IV. Discussions

The different regimes of wing rock discussed above are summarized in the sketch in Fig. 8. Boundaries for the different regimes cannot be precisely identified at this point due to insufficient data. Figure 8 shows that wing rock can occur

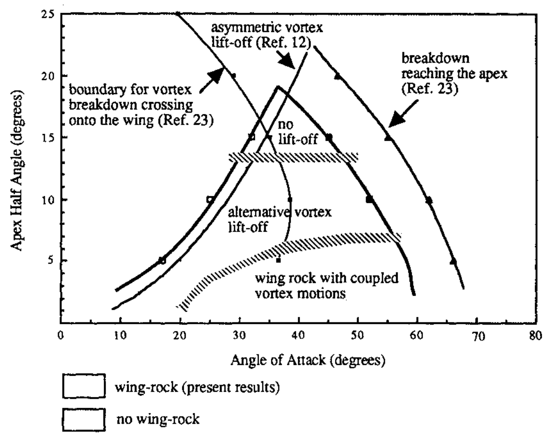

Fig. 8 Wing rock tendency of sharp-edge delta wings.

in the absence of asymmetric vortex liftoff (75- and 85-deg wings), vortex breakdown (80- and 75-deg wing), and static hysteresis (all wings). Thus these flow phenomena are not the necessary ingredients for wing rock. Rather the susceptibility to wing rock is determined by the vortex interaction as dictated by the strength and proximity of the leading edge vortices. The key interaction is at the apex region where the innermost portions of the vortices are formed and the vortices are closely spaced. This interaction creates the initial vortex asymmetry needed to induced a roll motion. The build-up or damping of the motion is then determined by the vortex behaviors at nonzero roll conditions, with time-lag being a major contributing factor. Once a sufficiently large roll moment is induced by the asymmetry in vortex strength, the side with the stronger vortex will start moving up while the other is moving down. The resulting changes in the effective apex angles will lead to corresponding decrease and increase in the rates of vorticity being fed from the leading edges to the upward and downward moving sides respectively. An aerodynamic spring for wing rock can be created due to the time-lag effect.

For the 80-deg wing, vortex liftoff is a major contributor for wing rock amplitude build-up. The combination of the induced sideslip during the roll motion and the time-lag effect makes vortex liftoff the dominant flow feature during wing rock. Contrary to the 80-deg wing, vortex liftoff is not a factor for the wing rock of the 75-deg wing. This is probably due to the larger apex angle, and thus the wing has to encounter a larger roll (sideslip) angle before vortex liftoff will occur. A possible cause for wing rock for the 75-deg wing is the dynamic response of vortex strength (and/or position) to the change in the effective apex angle. If the effective lift from the left and the right vortices on a wing become asymmetric due to, say, vortex interaction, the side with the lower lift will start to roll down. The vortex on the downward moving side will gain strength due to the increase in effective apex angle (and possibly also from the wing motion) while the opposite happens on the upward moving side. If the vortex strength adjustment is rapid compared with the wing motion, the rolling motion will be damped and no self-sustained wing rock will occur. If the vortex strength adjustment is slow compared with the speed of wing motion, however, a time lag will occur between the vortex strength and the wing motion. Thus the downward moving side will maintain a lower-than-expected lift for a period of time until the vortex readjusts with a gain in strength. On the upward moving side the lift will maintain a higher-than-expected value until the vortex again readjusts but with a lowering in strength. Hence the induced roll-moment will allow a buildup of the rocking amplitude. At very high sweep angles such as in the case of the 85-deg wing, the vortex spacing is very small and the interaction between the vortices becomes so strong that at higher angles-of-attack the motions of the two vortices are strongly coupled, resulting in the observed erratic rocking behaviors.

The response of vortex breakdown to changing flow conditions is evidently rather slow. At high oscillation rates, the breakdown location remains essentially fixed. Thus, the breakdown location on the downside of the wing can be at a farther aft location (corresponding to a certain average location) than at the corresponding static situation. Hence additional lift will be induced on this side of the wing due to the delay in breakdown. At the same time, the vortex on the upside will break down at a farther forward position. Thus at dynamic situation less lift will be induced on this side. This may increase the roll moment for the building up of the wing-rock amplitude. The time-lag effect of vortex breakdown may also be the reason for the amplitude overshoot during the buildup phase observed by Arena and Nelson.[18]

Hence wing rock is initiated by vortex interaction which results in asymmetries in the vortex strength and sustained by the time-lag effect. Phenomena such as vortex lift-off and vortex breakdown are vortex behaviors that occur naturally as dictated by the flow conditions. While these phenomena are not the causes of wing rock, their presence, especially when associated with time lag, have great influence on the behavior of wing rock.

V. Summary and Conclusions

The wing rock for several different delta wing planforms was investigated using flow visualization in a water tunnel. By studying and comparing flows for free oscillation, forced oscillation, and static situation, valuable insights on the causes and characteristics of wing rock have been gained. The main observations are summarized below:

1) Steady, regular wing rock for the 80-deg wing is characterized by the alternate liftoff and reattachment of the leading edge vortices.

2) For the 85-deg wing at high angles of attack, vortex interaction due to the close proximity of the vortices can cause irregular wing rock motions. Wing rock can be sustained by combinations of various forms of vortex asymmetry.

3) For the 75-deg wing, vortex dynamic response can lead to wing rock even in the absence of vortex liftoff.

4) Contrary to some previous results, vortex liftoff was never observed at static zero-roll conditions for all the wings tested. The reasons for this discrepancy are not known at this point. During dynamic situations, vortex liftoff becomes a prominent feature for the 80-deg and 85-deg wings throughout the oscillation cycle due to the time-lag effect.

5) The time-lag associated with vortex position is dependent on the oscillation rate and chordwise position. Time-lag can result in the existence of partial liftoff and breakdown on the same vortex, as opposed to during static situations where the two phenomena seem to be mutually exclusive.

6) Both the vortex liftoff and reattachment processes occur initially at the apex region. This leads to an interesting question of whether wing rock can be prevented or its amplitude be attentuated on the 80-deg wing if suitable modifications are imposed at the apex so the liftoff is prevented at that region.

Perhaps the most important conclusion that can be drawn from this study is that, rather than just vortex liftoff or flow hysteresis, a large number of flow phenomena can generate various forms of wing rock. Thus the problem can exist in many situations where one may not expect it to.

Acknowledgments

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