ICAS-82-6.7.5

FUSELAGE EFFECTS IN LEADING EDGE VORTEX FLAP AERODYNAMICS

James F. Marchman, III* and Mark L. Hollins**
Virginia Polytechnic Institute and State University
Blacksburg, Virginia, USA

ABSTRACT

Wind tunnel tests were conducted to determine the influence of a fuselage on the aerodynamic behavior of a 60° delta wing with leading edge vortex flaps. The results showed that at some combinations of angle of attack and yaw the fuselage had a stabilizing effect on the leading edge vortices and that $C_L max$ is increased due to fuselage lift and added vortex stability. The fuselage did not affect the ability of vortex flaps to significantly increase the L/D of the wings.

INTRODUCTION

Many of today's supersonic dash aircraft and all proposed supersonic cruise aircraft rely on highly swept delta wings to provide needed lift with acceptable drag levels at supersonic speeds. Unfortunately, such highly swept wings are not very efficient at subsonic speeds due to their low aspect ratios. At subsonic speeds much of the lift of a highly swept delta planform is "vortex lift" resulting from the vortex formed by flow separation about the wing's leading edge.

The leading edge vortex is a major contributor to the aerodynamic forces and moments on a highly swept wing. The vortex (Figure 1) contributes "vortex lift" due to its low pressure and contributes to the potential lift by keeping the flow over the wing attached at high angles of attack. This flow is fairly well understood and has been described analytically by Polhamus[1] and others. The primary drawback of such vortex lift is its associated high drag.

The concept of the leading edge vortex flap (LEVF) involves moving the vortex from the upper surface of the wing onto a leading edge flap. The flap is deflected as far as possible without preventing separation, since without separation no vortex could form, and the flap is sized to result in flow reattachment at the flap/wing hinge line. The result is a forward tilting force vector or a thrust due to the low pressure in the vortex. The resulting thrust can greatly improve lift-to-drag ratios for wings equipped with LEVF. Results of some studies on the LEVF concept have shown L/D improvements of 40% or more [2,3,4]. Therefore, by using LEVF a swept or delta wing aircraft can greatly improve its performance in climb, cruise or maneuvers.

Previous published results from tests of LEVF have been confined to tests of a wing alone or a wing with a small centerbody to house a sting balance[2,3,4]. The present study was undertaken to examine the aerodynamic improvement possible on a 60° delta wing/fuselage combination with several LEVF configurations.

While some LEVF research has concentrated on the 74° sweep configuration planned for supersonic cruise aircraft[2], this research investigated the 60° sweep case which is more common for existing delta wing fighter aircraft. Hence, the results should be relevant for studies of new aircraft designs as well as of modifications of existing aircraft.

In addition to tests on downward deflected LEVF, a study of inverted or upward deflected LEVF (ILEVF) was desired. This concept, which had also been previously investigated for the wing alone case[5], allows the development of a strong leading edge vortex at low wing angles of attack; hence, giving a large vortex lift at angles of attack where it would not normally exist. The advantage of ILEVF would be the generation of increased vortex lift on the take-off roll within the limits of conventional tail scrape angles. ILEVF use would also allow steeper approaches to landings with lower angles of attack, thus improving pilot visibility over the nose of the aircraft.

Of primary concern in this research was the effect of the fuselage on stability in yaw. A previous study of yaw effects on a 60° delta wing with LEVF[6] indicated that yaw angles up to 20° did not seriously degrade the performance found with leading edge vortex flaps and, in fact, rolling tendencies in yaw were decreased with LEVF use. It is important to determine whether the effects of the fuselage on the flow over the wing will alter these findings.

Leading edge vortex stability is very sensitive to wing sweep angle; hence, as a wing is yawed and effective sweep angles change, the result may be a strengthening of the vortex over the more highly swept leading edge and a weakening or even bursting over the wing of the other vortex. This condition may result in severe roll problems in yaw as well as other stability problems. Previous studies[7,8] have shown that vortex breakdown at high angles of attack can cause large destabilizing effects on the stability of delta wings. Since leading edge vortex flaps are designed to position the vortices over the flap rather than over the wing surface, the effect of yaw and angle of attack on stability is somewhat different from that on non-flapped delta wings.

The presence of a fuselage may alter stability behavior of delta wing - LEVF combinations due to flow blockage by the fuselage in yaw shielding the downstream wing and also due to the flow straightening effect of the fuselage. Hence, this study was undertaken to examine the difference in the aerodynamics of a 60° delta wing with leading edge vortex flaps seen between tests of the wing alone and the wing with a typical fuselage configuration.

DESCRIPTION OF EXPERIMENT

Tests were conducted to compare the behavior over a range of angle of attack and yaw angles of a

* Wind Tunnel Director, Associate Professor of Aerospace Engineering, Associate Fellow of AIAA,
**Research Assistant, Student Member AIAA

60° delta wing-fuselage combination with earlier data taken for a 60° delta wing alone[6]. The basic model used in the tests was a revolved cylindrical fuselage with a center mounted 60° delta wing as shown in Figure 2. No vertical or horizontal stabilizer or canards were added to the fuselage. Hence, all experimental results are for the wing-fuselage combination only.

The two flap planforms are also shown in Figure 2. These consist of a constant chord leading edge flap of three inch chord and an inversely tapered flap with a three inch chord at the wing tip. The downward deflected (LEVF) flap cases were run at a flap deflection angle of 30° which had been shown effective in previous tests[3]. The constant chord and tapered flaps were also tested in the inverted position giving a 30° ILEVF case.

All tests were run in the Virginia Tech Stability Wind Tunnel at a Reynolds number of approximately 2 X 10^6. The tunnel has a 6 X 6 foot closed test section and has flow turbulence levels of less than 0.05 percent. Models were sting mounted on a six component strain-gauge balance system. Each configuration was tested through a range of angles of attack from zero to fourty-five degrees. Data was collected, analyzed and plotted by the facility's Hewlett-Packard 9825 Data Acquisition System.

DATA AND RESULTS

All data is presented in the usual coefficient form. It should be emphasized that all coefficients are calculated using the wing projected area plus the projected area of the flaps. The flap area used is the actual flap area multiplied by the cosine of the flap deflection angle. The resulting coefficients therefore show only the aerodynamic effects of the flaps since any effect due to their added area has been divided out. Pitching moments are calculated about the mean quarter chord which, for a delta wing, is at the centerline half-chord.

Figures 3, 4 and 5 show the basic effects of leading edge vortex flaps on the wing-fuselage combinations at zero yaw, while Figures 6 and 7 compare the cases with and without fuselage for the constant chord LEVF case at zero and ten degrees yaw.

Figure 3 shows the effects of the two LEVF configurations tested with the wing-fuselage combination on lift coefficient. The effect is essentially negligible when the added flap area is divided out in the lift coefficient. The primary action of the LEVFs is to take the force vector, which is tilted rearward on the normal wing, and tilt it forward by moving the vortex to the flap. The potential lift of the wing is largely unaffected while the vortex lift is only slightly altered. At low angles of attack less of the vortex force acts in the lift direction when LEVF are used, hence there is a slight reduction in C_L at low α with LEVF. The constant chord LEVF result in better lift near $C_{L_{max}}$ but give slightly lower C_L at low α.

The primary effect of LEVF is to reduce drag by producing a thrust due to the forward tilt of the vortex force vector. Figure 4 shows the plot of C_D vs C_L for the LEVF tested and the basic wing-fuselage model. While it is difficult to determine from the plot at low C_L values, it can be seen that at most values of C_L both LEVF configurations give a lower C_D than found in the basic wing-fuselage case. The constant chord LEVF gives somewhat lower values of C_D than the tapered LEVF. This appears to occur due to the ability of the constant chord flaps to contain the vortex on the flap more effectively than the tapered LEVF.

The combined effect of the LEVF on lift and drag and, hence, on airplane performance, is seen in a plot of lift-to-drag ratio versus lift coefficient as shown in Figure 5. This data shows the L/D improvement due to LEVF to be substantial; as much as 55 percent at angles of attack around 10°! Previous tests on wings alone have shown even greater improvements[3,4] but in the present tests, the influence of the fuselage tempers the results. In these results, again the constant chord LEVF appear superior to the tapered flaps, although not markedly so. The weight and size advantage of the smaller, tapered flaps may outweigh their slightly lower performance disadvantage when compared to the constant chord LEVF.

In Figures 6 and 7 it is clear that the primary effect of the fuselage is to increase C_L max. There is a negligible effect of the fuselage on lift at lower angles of attack and on drag at both yaw angles. It is also evident that yawing the model ten degrees results in slightly earlier stall and a lower C_L max but there is no indication that the fuselage or 10° yaw causes any reduction in LEVF effectiveness. Similar effects were seen in the tapered LEVF case.

The increase in C_L max appears to result from a stabilizing effect of the fuselage on the flow at near-stall angles of attack. The fuselage apparently helps maintain a straight flow over the wing and discourages vortex bursting which leads to stall.

Since lift and drag behavior were not significantly changed by the addition of a fuselage one would expect little effect on pitching moment as long as the fuselage is centered about the moment center. This was found to be the case so no comparisons will be presented graphically. The pitching moment data for the base wing-fuselage and that with constant chord and tapered LEVF are shown in Figure 8. As in earlier tests[3,4] it was found that the use of constant chord LEVF give a substantially different pitching moment behavior from the tapered LEVF which closely parallel the base wing data. This is due to the strong effect of the vortices on the added flap area near the wing apex in the constant chord LEVF case. Yaw of the models up to ten degrees produced negligible changes in the pitching moment behavior.

One would expect the most pronounced effects of yawing the model and, hence, of fuselage flow blockage in yaw, to appear in the sideforce, rolling and yawing moment data and this is, indeed, the case. Figure 9 presents data for the wing with no flaps, both with and without fuselage, at zero and -10° yaw. The zero yaw data evidences a slight asymmetry in the flow on the no fuselage case where at -10° yaw a slight sideforce is seen to develop. With the fuselage there is no sideforce at zero yaw until an apparent asymmetric vortex bursting near and beyond stall results in a sideforce on the fuselage at large angle of attack. At various ten degrees yaw a negative sideforce develops on the fuselage which is magnified in stall. The constant chord LEVF data (Figure 10) exhibits similar effects at high angles of attack but at low angles of attack it appears that the vortex flaps produce a negative sideforce in yaw. Here the vortices acting on the flaps produce a strong force in the negative sideforce direction due to the relative strength of the two vortices. These results were seen to a lesser degree with the tapered LEVF because of the reduced flap size.

Since vortex flaps produce little force which would contribute to a yawing moment no major effect other than that due to the fuselage was expected. Figure 11 shows the effect of the presence of the fuselage in yaw on the wing with no flaps. The only effect noted here is a yawing moment which develops at or near $C_{L_{max}}$ which is apparently due to the wing's separated wake blocking out the aft section of fuselage at high angles of attack resulting in a yaw due to side forces on the nose of the fuselage. This agrees with the increased sideforces seen at high angles of attack on the yawed wing fuselage case seen in Figure 9.

The primary data which exhibited an effect of the yawed fuselage on forces produced by flow over the LEVF is for rolling moment. At ten degrees of yaw one wing is essentially swept 50 degrees and the other, 70 degrees, resulting in leading edge vortices of differing stability. The vortex on the lower swept side will burst earlier at high angles of attack. At the same time, the wing with lower sweep has an effectively higher aspect ratio and greater potential lift. Therefore, a rolling moment may result due to the relative strengths of the increased vortex lift on the side of the wing with increasing sweep and the increased potential lift on the other side of the wing. The presence of a fuselage may affect this by helping stabilizing the flow on the "upwind" wing while acting as a "fence" and by destabilizing the flow and vortex on the "downwind" wing due to the fuselage wake.

Figure 12 shows the effect of yaw on rolling moment for the base wing with and without the fuselage. It appears that at lower angles of attack the potential lift increase on the side with lower sweep dominates the vortex lift increases on the other side. As stall is approached this potential lift becomes less dominant causing a reversal in the slope of the curve until the high drag due to earlier stall on the "upwind" wing causes a large increase in roll. The addition of a fuselage does not influence these trends at lower angles of attack; however, it does appear to delay the stall of the upward wing and, hence, the resulting change in rolling moment at high angles of attack.

Similar behavior is seen in the data for the wing with constant chord and tapered LEVF as shown in Figures 13 and 14. It is seen however, that LEVF result in a rolling moment due to yaw at zero angle of attack. This is obviously due to the downward force on the "upstream" flaps. At higher angles of attack the behavior is seen to be like that of the plain wing but with the upturn or discontinuity of the yawed case curve shifting to a higher angle of attack for the constant chord flap case, a result obviously due to the later stall noted with constant chord LEVF.

A closer look at the roll data for the wing-fuselage cases in yaw is given in Figure 15 for the constant chord LEVF case. It is seen that the most erratic roll behavior occurred at five degrees of yaw where the balance of the downwind wing vortex forces and upwind wing potential flow forces is apparently much more delicate.

Inverted leading edge vortex flaps (ILEVF) exhibit much the same results as the downward deflected LEVF. The primary purpose of ILEVF is to shift the lift curve to the left at low angles of attack and, as shown in Figure 16, this occurs with the fuselage present just as it did in earlier tests with only a wing[5]. Higher drags result with ILEVF. Again the C_L max with the fuselage is greater than without[5]. Sideforces in yaw behave similarly to regular LEVF as do pitching moments and yawing moments; hence, this data is not shown. Earlier stall with ILEVF causes all stall related effects such as the curve discontinuity for rolling moment to occur at lower angles of attack as seen in Figure 17 for constant chord LEVF with fuselage.

CONCLUSIONS

From these results one can conclude that leading edge vortex flaps do not substantially alter the stability characteristics previously found on plain delta wings. The presence of the fuselage does apparently help stabilize the upwind vortex in yaw and consequently produces some change in rolling moment behavior near stall by retarding stall on the upwind wing.

These results further verify the usefulness of leading edge vortex flaps as a means of improving the low speed performance of delta wings. The leading edge vortex flap is shown to give L/D improvements as much as 55 percent which translate to equal improvements in all aspects of aircraft performance.

REFERENCES

1. Polhamus, E. C., "Predictions of Vortex Lift Characteristics by a Leading Edge Suction Analogy", Joul. of Aircraft, Vol. 8, April 1971.

2. Rao, D. M., "Leading Edge Vortex-Flap Experiments on a 74° Delta Wing", NASA CR-159161, Nov. 1979.

3. Marchman, J. F., Plentovich, E. B. and Manor, D., "Performance Improvement of Delta Wings at Subsonic Speeds Due to Vortex Flaps", AIAA Paper 80-1802, AIAA, August 1980.

4. Marchman, J. F., "Effectiveness of Leading-Edge Vortex Flaps in 60 and 75 Degree Delta Wings", Journal of Aircraft, Vol. 18, April 1981, pp. 280-286.

5. Marchman, J. F., "The Aerodynamics of Inverted Leading Edge Flaps on Delta Wings", AIAA Paper 81-0356, AIAA, January 1981.

6. Marchman, J. F. and Thomas, R. H., "Effects of Yaw on Leading Edge Vortex Flap Aerodynamics", AIAA Paper 81-1660, AIAA, August 1981.

7. Johnson, J. L., Grafton, S. B. and Yip, L., "Exploratory Investigation of the Effects of Vortex Bursting on the High Angle-of-Attack Lateral-Directional Stability Characteristics of Highly-Swept Wings", AIAA Paper No. 80-0463 AIAA, March 1980.

8. Erickson, G. E., "Flow Studies of Slender Wing Vortices", AIAA Paper No. 80-1423, AIAA, July 1980.

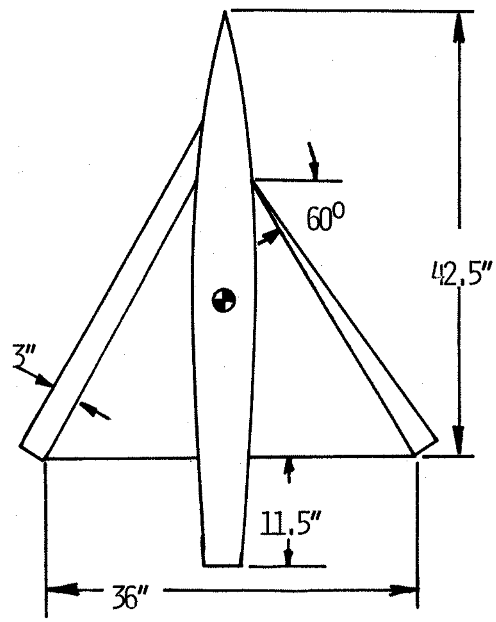

Figure 2: Model Configurations

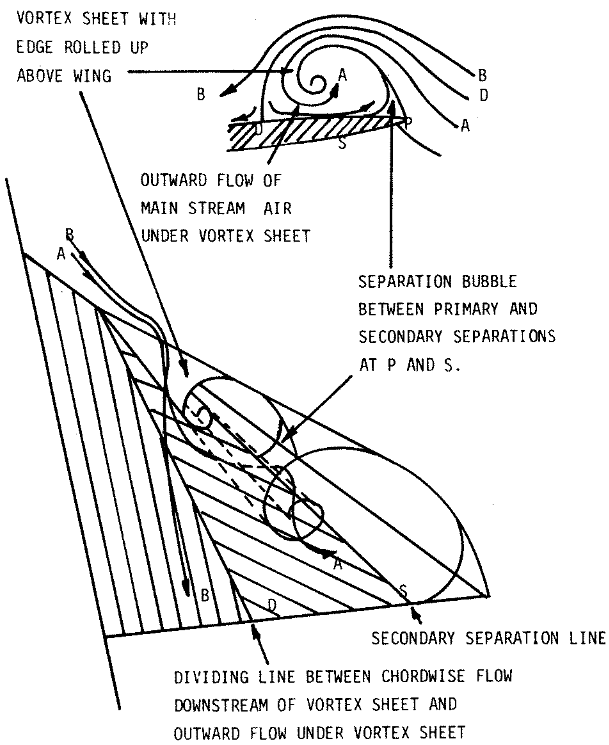

FIGURE 1: Schematic of Flow Over a Delta Wing.

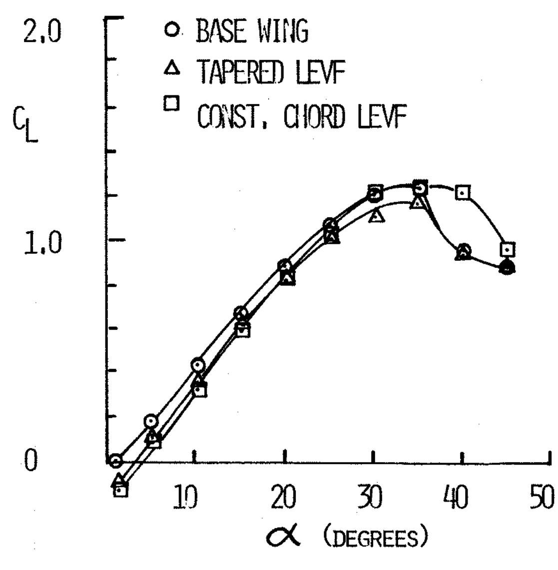

Figure 3: LEVF Effects on Lift

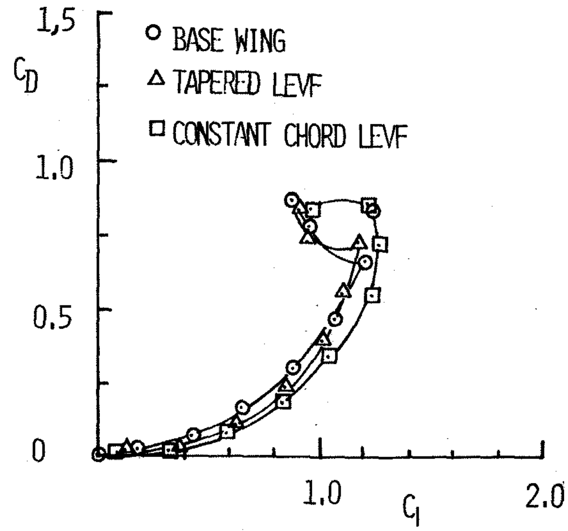

Figure 4: LEVF Effects on Drag

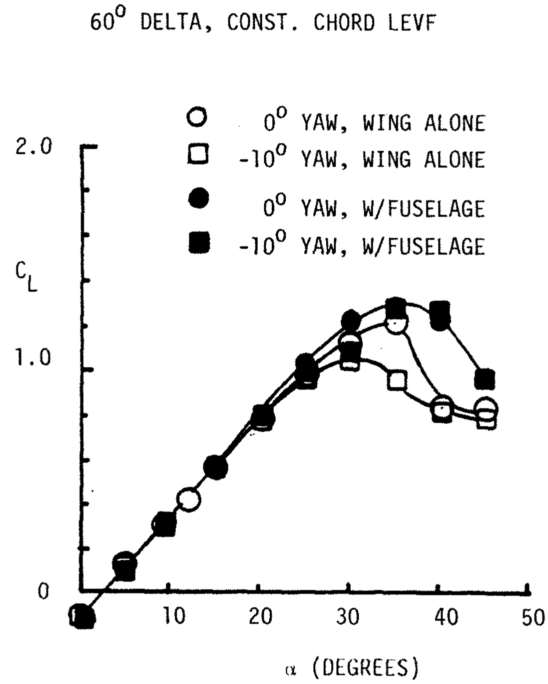

Figure 6: Fuselage and Yaw Effects on Lift with Const Chord LEVF

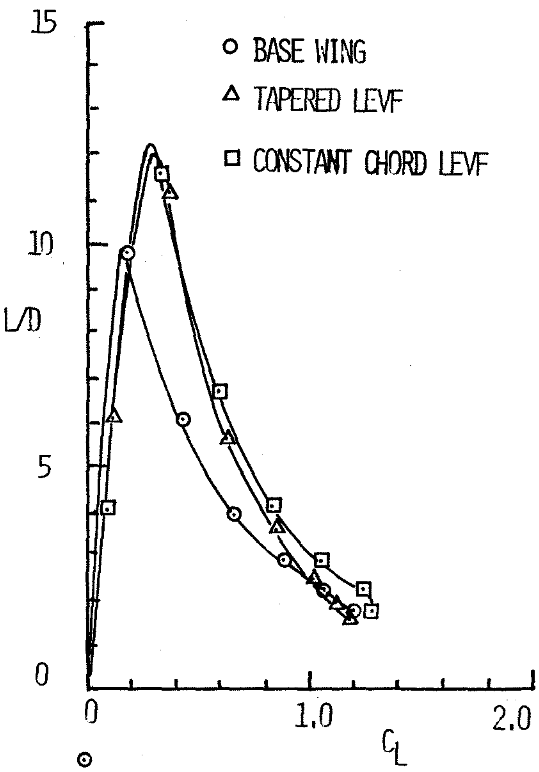

Figure 5: LEVF Effects on L/D

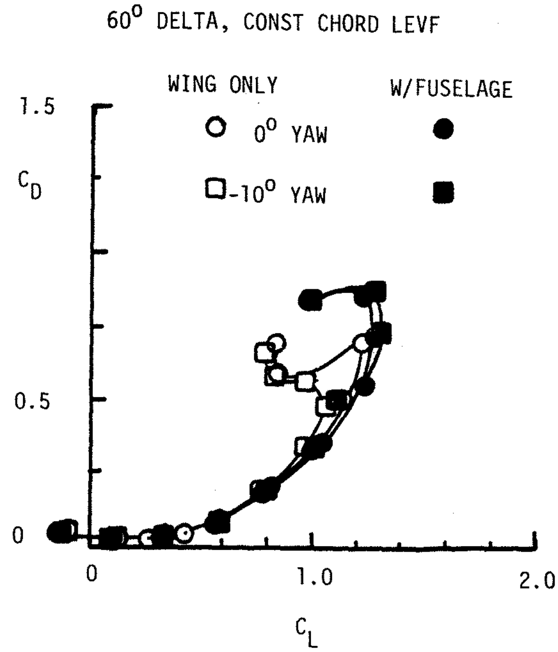

Figure 7: Fuselage & Yaw Effects on Drag with Constant Chord LEVF

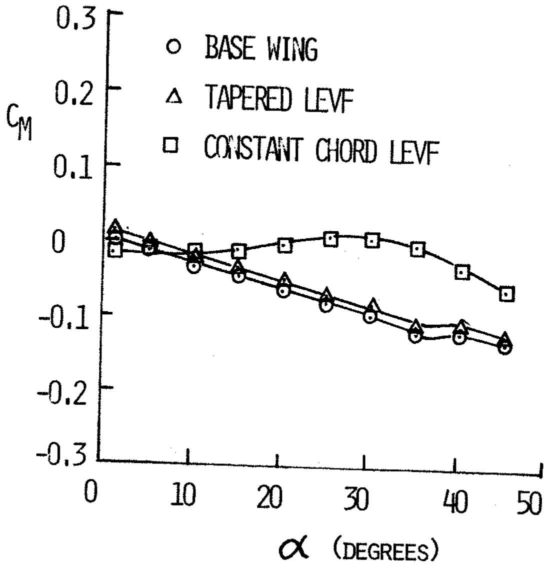

Figure 8: LEVF Effects on Pitching Moment

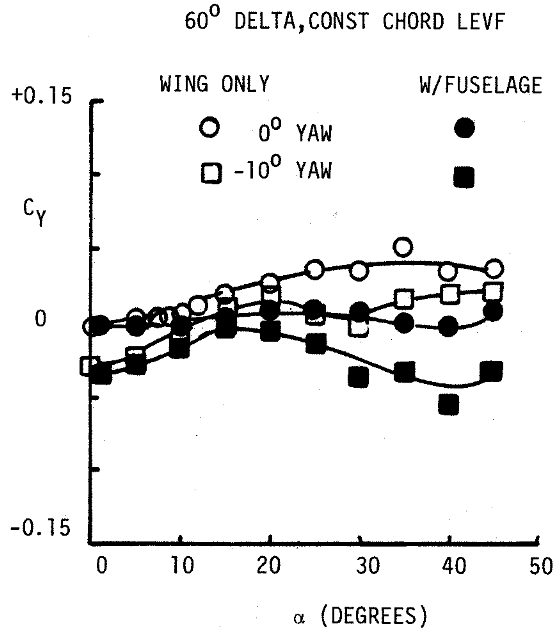

Figure 10: Fuselage and Yaw Effects on Sideforce with LEVF

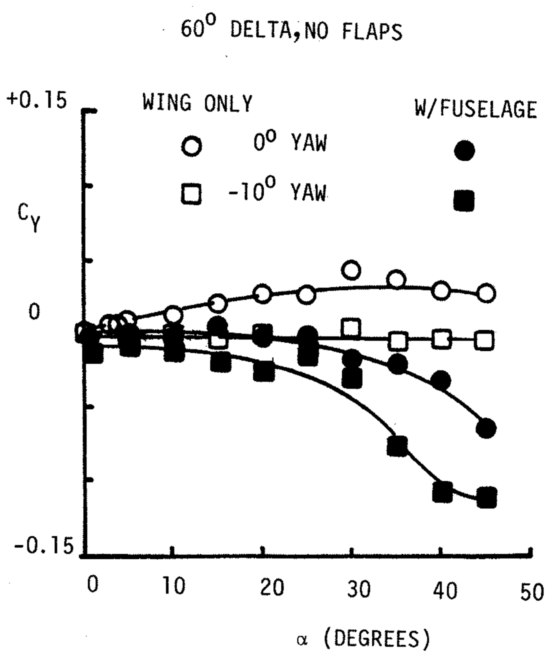

Figure 9: Fuselage and Yaw Effects on Sideforce with No Flaps

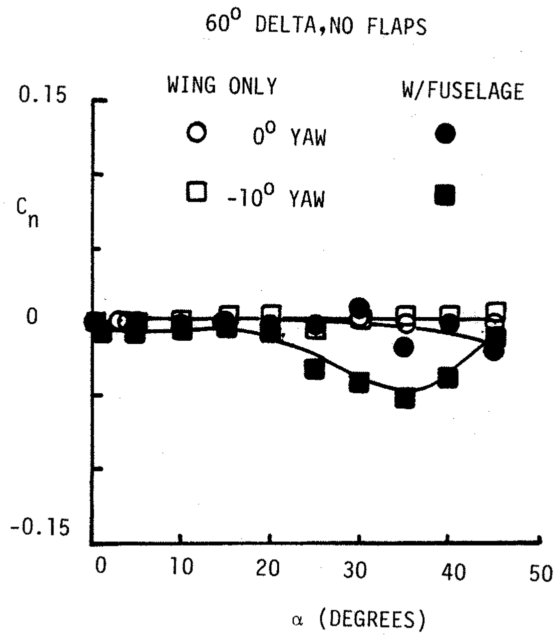

Figure 11: Fuselage and Yaw Effects on Yawing Moment with No Flaps

60° DELTA, NO FLAPS

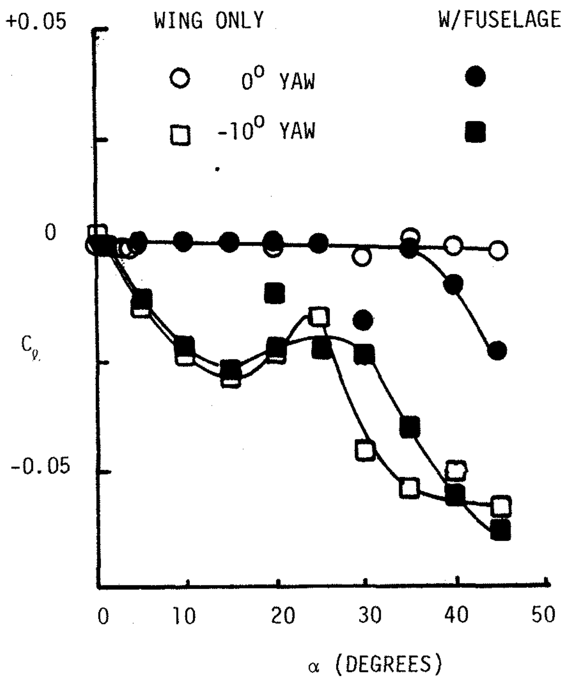

Figure 12: Fuselage and Yaw Effects on Roll with No Flaps

60° DELTA, CONST CHORD LEVF

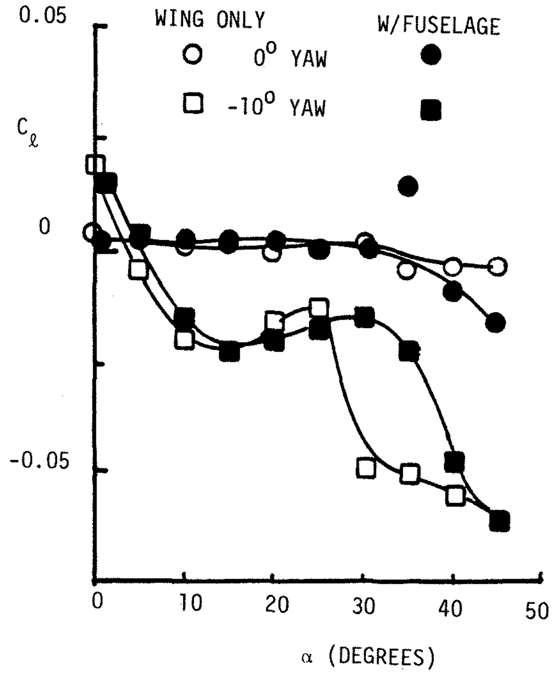

Figure 14: Fuselage and Yaw Effects on Roll with Constant Chord LEVF

60° DELTA, TAPERED LEVF

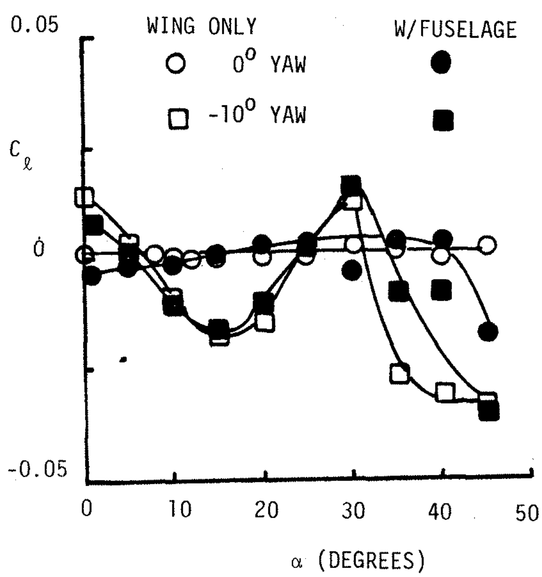

Figure 13: Fuselage and Yaw Effects on Roll with Tapered LEVF

60° DELTA, CONST CHORD LEVF

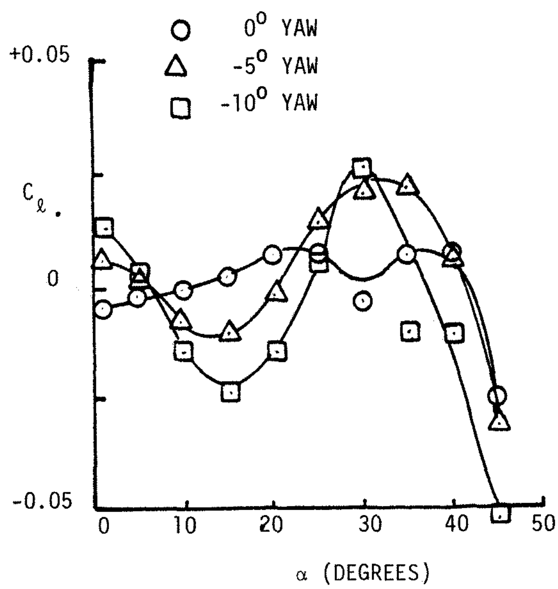

Figure 15: Rolling Moment with Constant Chord LEVF in Yaw

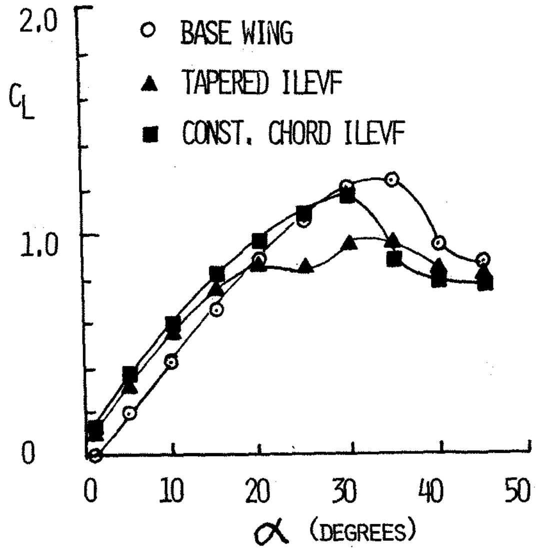

Figure 16: Inverted LEVF in Lift

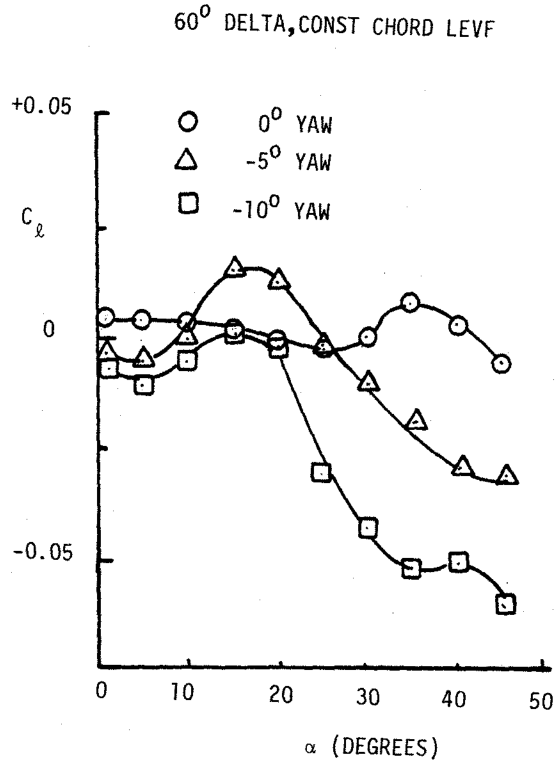

Figure 17: Rolling Moments for 1 LEVF in Yaw