ICAS-94-4.6.5

A LEX BLOWING TECHNIQUE FOR POST-STALL ROLL MANEUVERABILITY

Dhanvada M. Rao* and Gautam Sharma**
ViGYAN Inc., 30 Research Drive, Hampton, Virginia, USA

ABSTRACT

A low-speed wind tunnel investigation was conducted of a LEX blowing concept aimed at maximum-lift and high alpha roll-control enhancements on a generic fighter configuration. Lateral ejection from LEX leading-edge slots was employed for vortex augmentation, to improve the trapezoidal-wing stall characteristics; one-side LEX blowing was used for roll control. Salient results are presented of flow visualizations and pressure/force/moment measurements, verifying vortex flow management achieved by LEX blowing and demonstrating the consequent roll-control augmentation in the post-stall alpha range 30^0 to 50^0 where the aileron effectiveness was substantially degraded.

NOMENCLATURE

A_{REF}	Wing Reference Area (sq. in.)
C_L	Lift Coefficient
C_l	Rolling Moment Coefficient (body axis)
$C_{l,S}$	Rolling Moment Coefficient (stability axis)
$C_{P,U}$	Upper-Surface Pressure Coefficient
C_μ	Blowing Momentum Coefficient ($= m.V_J/q.A_{REF}$)
c	Local chord (in.)
m	Massflow Rate (pounds/sec.)
q	Freestream Dynamic Pressure (pounds/sq. ft.)
V_J	Jet Exit Velocity (feet/sec.)
α	Angle of Attack (deg.)

INTRODUCTION

Leading-edge extensions (or LEX's) are well known passive devices for improving the maximum lift and maneuver capabilities of supersonic fighter configurations employing thin, low aspect-ratio trapezoidal or diamond wing planforms (e.g., F-16, F-18, and F-22). At moderate angles of attack, interaction of LEX-generated longitudinal vortices controls flow separation on the moderately swept primary lifting surfaces, thus alleviating wing stall as well as providing additional vortex lift directly on the LEX's. With increasing alpha however, onset of vortex breakdown on the wings abruptly terminates the lift benefit of LEX's; this rapid onset of stall is accompanied by pitch-up, aero-dynamic asymmetries and buffet. The concerted action of above mentioned post-breakdown effects creates a power-ful tendency for roll/yaw departure and handling difficulties. Mitigation of vortex breakdown effects and enhancement of roll-control at and beyond $C_{L,max}$, are recognized to be among the important aerodynamic challenges for next-generation combat aircraft.

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* Principal Vice President, Associate Fellow, AIAA

** Research Engineer; Member AIAA

Advanced LEX concepts, involving direct vortex manipulation at high alpha while retaining the lift benefit of fixed LEX's in low-to-moderate alpha range, are of considerable interest for future tactical aircraft designers. Active or 'smart' LEX's aim to alleviate high-alpha instabilities and low-frequency dynamics (e.g., wing rock) engendered by LEX-vortex breakdown, while improving post-stall maneuverability beyond the control limit of conventional trailing-edge and aft-tail surfaces. This objective motivated the earlier investigations of articulated, e.g., hinged or pivoted LEX's (refs. 1, 2). While actuated LEX's were shown to be potentially effective, they also produced non-linear control characteristics and significant cross-coupling effects; highly loaded movable LEX surfaces also pose structural and actuation problems. The mechanical complexities associated with articulated surfaces for vortex control might be avoided by the use of pneumatic techniques, such as axial blowing which stabilizes the vortices and delays their breakdown (refs. 3). Although axial blowing has been demonstrated by several investigators to improve $C_{L,max}$, its application for high-alpha vehicle control via nonsymmetrical vortex manipulation appears not to have been pursued.

An alternate pneumatic approach towards LEX vortex control is proposed herein. A high-momentum fluid sheet is ejected laterally from narrow slots located along the LEX edges, to directly control vortex sheet roll-up and thus the vortex strength. Whereas the axial injection technique for vortex stabilization can become effective only after onset of breakdown, the proposed lateral sheet blowing method should be operative immediately with LEX vortex initiation and continue past its breakdown. Consequently, a significant portion of the maneuvering flight envelope might be controllable by means of this active LEX technique.

Spanwise sheet blowing for vortex control on delta wing leading edges was studied nearly 30 years ago (ref. 4). A typical result (taken from ref. 4) is shown in fig. 1 where total pressure surveys taken in cross-flow plane show the vortex augmentation effect of full-span leading edge slot blowing, in comparison with the nonblown case. While the efficacy of lateral sheet blowing was confirmed, the associated momentum requirements were found to be excessive relative to the lift gain. A basic reason for this limitation was the outward displacement of blown vortex which tended to move the induced suction off the wing surface. In the present case however, blowing is applied to a relatively small fraction of the overall lifting surface, the LEX area typically being 10% of the wing area. The pneumatic mass rate requirement accordingly was expected to be reduced to a more practical range, and also any lateral vortex displacement was thought not to materially affect lift augmentation on the main wing surfaces. This expectation is based on the flow mechanism underlying LEX effect (ref. 5), according to which the lateral velocity component due to the LEX vortex directed outwards acts to increase the aerodynamic sweep-back of the wing leading edge. This induced effect promotes origination of a kink vortex at the LEX/wing junction, which serves to energize the wing upper-surface flow. LEX blowing was anticipated to sustain an active kink vortex to higher angles of attack thus improving post-stall lift capability (fig. 2). Asymmetric (or one-sided) LEX blowing will accordingly generate additional rolling moment, compensating for the stall degraded aileron power thus improving high-alpha roll control.

This paper discusses the salient results of a low-speed wind tunnel investigation of the above LEX blowing concept on a complete generic fighter configuration. The present work was an extension of preliminary studies of a simplified wing-alone model which showed promising results (ref. 6). Flow visualizations, limited pressure measurements and six-component force and moment evaluations were conducted in a wide angle-of-attack range and at zero sideslip. The effects of varying blowing momentum rate and part-length LEX slots were explored in some detail.

EXPERIMENTAL DETAILS

The test model was a generic fighter configuration, including twin vertical and horizontal tails, shown in fig. 3. The model contained flow channels conveying pressurized air from external blowers via flexible hoses to the LEX plenum chambers. The plenums exhausted through narrow slots located along the LEX leading edges, producing thin jet sheets directed spanwise. Selected portions of the LEX slots were sealed with tape to simulate symmetrical (i.e., both sides), or one-sided 'front-half- slot' or 'rear-half-slot' blowing arrangements. Control valves and flow meters were incorporated in the air supply lines to regulate and monitor LEX blowing massflow rates.

The model was mounted on a 6-component strain gage balance. Chordwise rows of pressure taps were installed on the upper surfaces and connected to an external Scani-Valve system. The LEX blowing momentum with one-side blowing was directly measured as a wind-off side force and calibrated versus the blower flow rate. This procedure, repeated with various slot length configurations, provided a more reliable measure of the momentum coefficient, including slot expansion effect due to 'ballooning' of the pressurized LEX plenum chambers. The maximum jet velocity was about 4 times the freestream velocity and therefore subsonic. The pressure and balance measurements were performed in ViGYAN 3 x 4 ft. low-speed wind tunnel at a freestream speed of 65 feet per second. The Reynolds number based on mean aerodynamic chord was 0.37×10^6. Smoke visualizations were performed (using a model built to half the scale of the force model) in ViGYAN 1.5 x 1.5 ft smoke facility, at a Reynolds number estimated at 4×10^4.

RESULTS & DISCUSSION

Smoke Visualizations

The initial smoke tunnel tests were aimed at obtaining a preliminary validation of the LEX blowing concept. The scope of the tests was limited to observing the influence of LEX blowing on kink vortex characteristics at increasing angle of attack. A pair of closely spaced nichrome wires was suspended vertically just upstream of the model nose tip and on either side of the symmetry plane. Liquid paraffin from a reservoir was allowed to trickle in droplets down the wires. When heated, the wires produced smoke sheets that were entrained by the LEX vortices. The spanwise position of wires was adjusted to allow sufficient smoke to be also drawn into the kink vortices. A transversely projected light sheet, intersecting the model at a forward (LEX) and an aft (wing) cross section captured the respective vortex flow patterns.

A series of visualization photographs with increasing angle of attack is presented in fig. 4. At each alpha, the un-blown case is compared with right-side LEX blowing. The LEX-station patterns show vortex magnification due to blowing. The corresponding wing station patterns reveal an intense kink vortex just outboard of the amplified LEX vortex on the right-hand side, compared with the opposite (i.e., un-blown) side where the kink vortex is relatively diffused or almost absent. Another view of the flowfield, looking from the right side of the model with the light sheet intersecting at right angle to the wing leading edge, is presented in fig. 5. Once again the kink vortex becomes clearly visible when LEX blowing is applied. To summarize, LEX blowing was able to reinstate the kink vortex at angles of attack when the unblown wing was fully stalled and the kink vortex absent. The re-established kink vortex interacted favorably with the initially stalled wing flowfield, generating a pronounced spanwise nonsymmetry with one-side LEX blowing, which can be expected to provide substantial rolling moments at post-stall angles of attack.

Pressures

In order to obtain a quantitative basis for the smoke visualization results, pressure measurements were made on wing upper surfaces at the semispan mid-positions. The primary objective was to confirm improvements in the upper-surface suction characteristics due to LEX blowing that would lead to lift increment. Also of interest was to compare front-half versus rear-half slot blowing on wing flow improvement. Typical results at angle of attack 30^0 (corresponding to $C_{L,max}$, as indicated by the force data shortly to be presented) are shown in fig. 6. In the absence of LEX blowing, the chordwise $C_{P,U}$ distributions are relatively uniform indicating complete stall. With right-LEX blowing, a suction peak develops near the right-wing leading edge, denoting an intensified kink vortex. Furthermore, at a constant momentum coefficient $c_\mu = 0.03$, blowing through the front-half slots is found to be more effective than blowing from rear-half slots, as measured by the respective $C_{P,U\ MIN}$ attained. The left-wing pressure distributions remain largely unaffected, indicating an absence of flow coupling between the blown and the unblown sides. Although limited in scope, these pressure results are fully in accord with the postulated flow model, and suggest that the spanwise lift asymmetry induced by one-LEX blowing can have significant rolling-moment potential at stall/post-stall angles of attack.

Forces & Moments

Extensive 6-component balance results were obtained to evaluate the LEX blowing effects, a selection from which is used to discuss the main trends. The lift and body-axis rolling moment characteristics versus angle of attack with front-half LEX slot blowing at $c_\mu = 0.03$ are shown in fig. 7. Noteworthy is the average lift improvement of about 15% in the post-stall alpha range of 30^0 to 45^0, together with a rolling moment coefficient of about .015, due to the right-wing lift increment. A comparison of rolling moments generated by blowing through front-half and rear-half LEX slots is shown in fig. 8. With reference to the pressure data already seen in fig. 6, these balance results affirm the advantage of front-half slot over the rear-half slot blowing. The LEX apex region where the vortex initiates is evidently a more fertile location for its control by blowing. The direct side-force due to LEX blowing also generates a proverse yawing moment, whose magnitude is greater in the case of front-half slot due to its greater moment arm. The body-axis rolling moment and the roll contribution due to proverse yawing moment combine to produce significantly improved roll power about the *velocity vector* in the case of front-half slot blowing, as also shown in fig. 8.

A compilation of balance rolling moment results with increasing blowing momentum at constant angles of attack is presented in fig. 9. Included are data pertaining to three different slot configurations, i.e., full-length, front-half and rear-half, with asymmetric LEX blowing in either direction. An incremental rolling moment (delta-c_l) which eliminates the initial baseline asymmetry at high angles of attack, is used for these comparisons. The incremental rolling moment is generally proportional to momentum coefficient, approaching saturation at $c_\mu = .03$ approximately. Again, the front-half slot consistently shows superior control than the rear-half slot. The structurally less desirable full-length slot shows little advantage aerodynamically in comparison with the front-half slot.

To put the lateral control capability of asymmetrically blown LEX in perspective, a comparison with aileron performance on this configuration is in order. Rolling moment data measured with 20^0 of ailerons are plotted versus angle of attack in fig. 10, including the zero-aileron case for reference. A pronounced rolling moment appearing between $\alpha = 30^0$ and 40^0 (i.e., a range straddling $C_{L,MAX}$) is characteristic of LEX configurations and attributed to onset of asymmetric vortex breakdown. This lateral disturbance is also reflected in the aileron characteristics. An 'average' rolling moment extracted from these non-symmetrical left and right aileron data indicates a declining aileron power with increasing alpha, dropping to a minimum value near $C_{L,MAX}$ when it is only about 1/3 of the $\alpha = 0^0$ roll capability. Although the roll power recovers at higher angles of attack, it remains substantially degraded in the post-stall region up to $\alpha = 40^0$; this high alpha loss of lateral control is a well known characteristic of this type of configuration.

Asymmetric LEX blowing with co-ordinated ailerons is an obvious means of boosting roll power. Results obtained with 20^0 ailerons in combination with front-half slot blowing at $c_\mu = 0.03$ are shown in fig. 11. These results indicate an almost two-fold improvement in the roll power between $\alpha = 30^0$ and 40^0. The additional rolling moment due to LEX blowing on the deflected aileron configuration is about the same as that generated on the 'clean' model, implying that the two roll control systems are aerodynamically uncoupled. Therefore, the roll control attributes of LEX blowing, e.g., sensitivity to momentum coefficient, linearity and control saturation etc. should remain valid for the case of its combined usage with ailerons.

CONCLUSIONS

A low-speed wind tunnel investigation including flow visualization, pressure and force/moment measurements, conducted on a generic fighter configuration model employing a blown LEX's concept, yielded the following salient results:

1. Lateral sheet blowing from LEX leading-edge slots reinstated a stable

LEX wing kink vortex at the angles of attack when unblown wing was fully stalled, thus creating a controllable means of stall alleviation and max-lift improvement.

2. One-side LEX blowing generates a pronounced asymmetry of spanwise lift distribution by controlling wing stall, thus producing a rolling moment in the post-stall alpha range.
3. The body-axis rolling moment is accompanied by a proverse yawing moment adding to the roll-power about the velocity vector.
4. Blowing through front-half of the LEX slot is equally or more effective as a full-length slot.
5. Roll control is essentially linear with blowing momentum coefficient and attains saturation at about $c_\mu = 0.03$.
6. LEX blowing in conjunction with ailerons doubles the roll power up to 20^0 alpha beyond $C_{L,MAX}$.

The investigation was exploratory in nature and subject to limitations usual to most proof-of-concept studies. Although the model represented a realistic aircraft configuration the test Reynolds number was modest; furthermore, LEX blowing was limited to subsonic (viz., unchoked) jet velocity. Nevertheless, the basic concept was validated and some promising quantitative aerodynamic effects demonstrated. Future investigations should remove these deficiencies and also include tests at angles of sideslip in order to explore the limits of control via LEX blowing across a full alpha-beta maneuver envelope.

ACKNOWLEDGEMENTS

This work was supported by NASA Ames Research Center under the Small Business Innovation Research Program, monitored by Mr. Larry A. Mein. The assistance of ViGYAN's wind tunnel personnel in preparing and conducting the test program is gratefully acknowledged.

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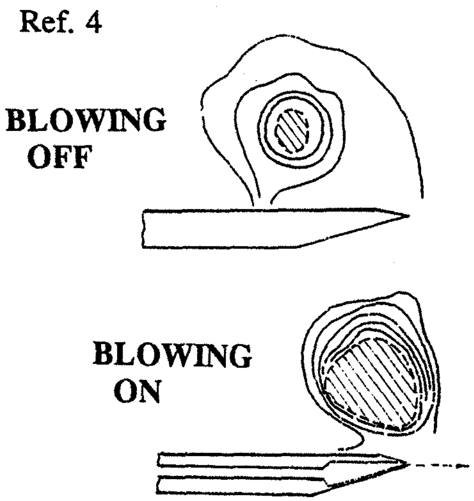
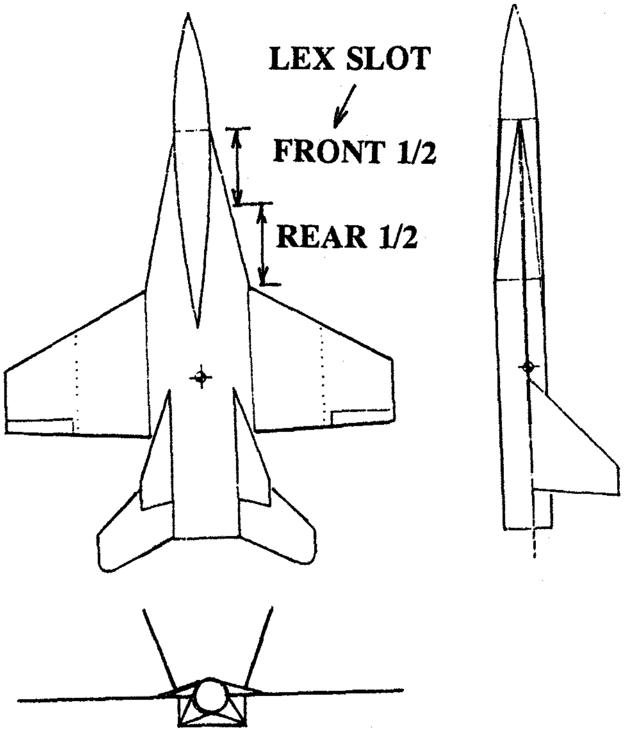


Fig.1 Leading Edge Blowing for Vortex Augmentation



SPAN = 23.85 in.
M.A.C = 10.51 in.
REF. AREA = 171.17 in^2
LENGTH = 32.12 in.

Fig.3 Model Configuration and Major Dimensions

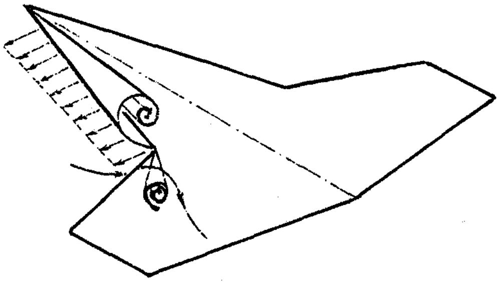


Fig.2 LEX Blowing Concept

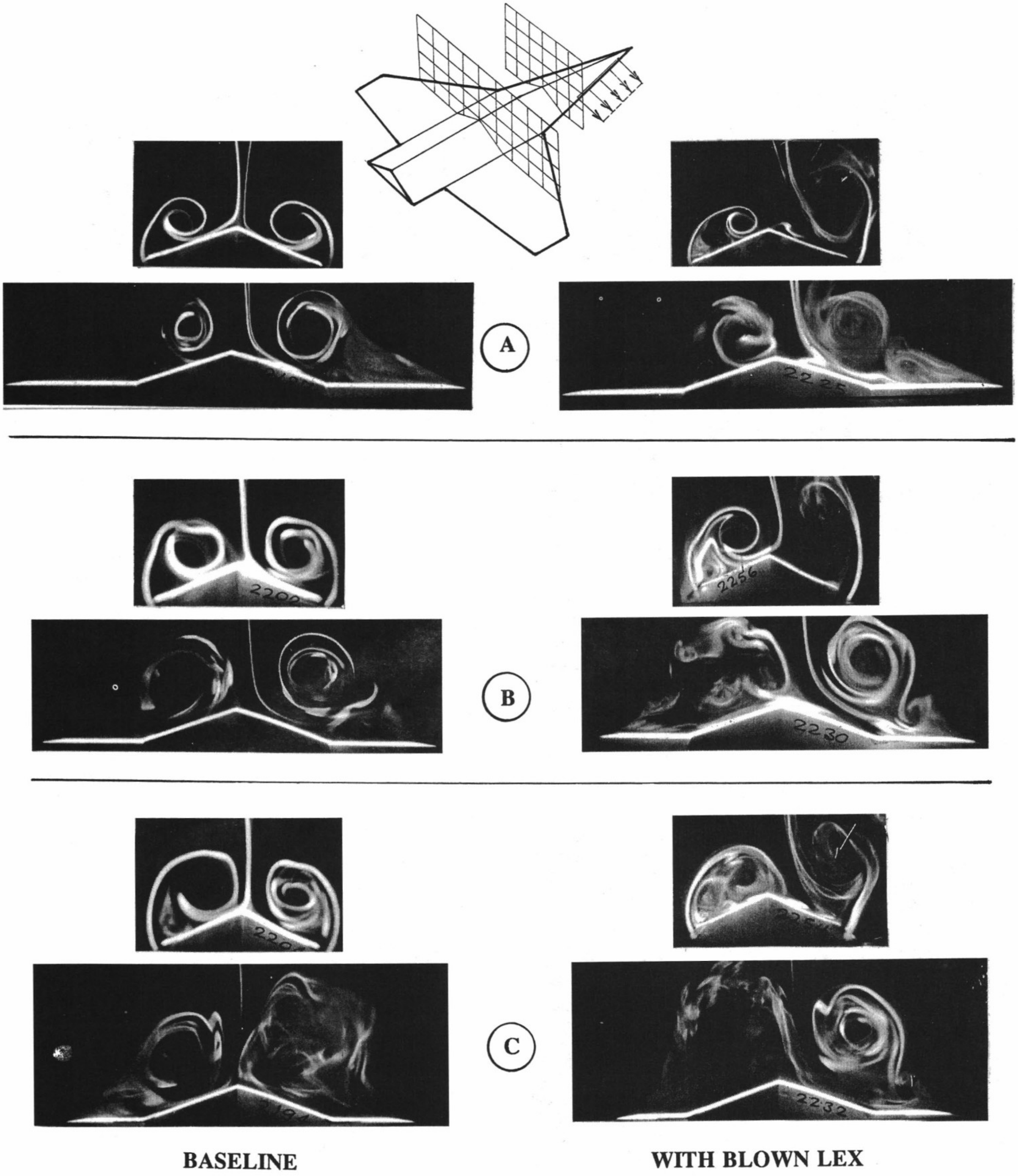


Fig.4 Smoke Visualizations With Right-Front-Half LEX Blowing
A. $\alpha=20°$; **B.** $\alpha=30°$; **C.** $\alpha=35°$

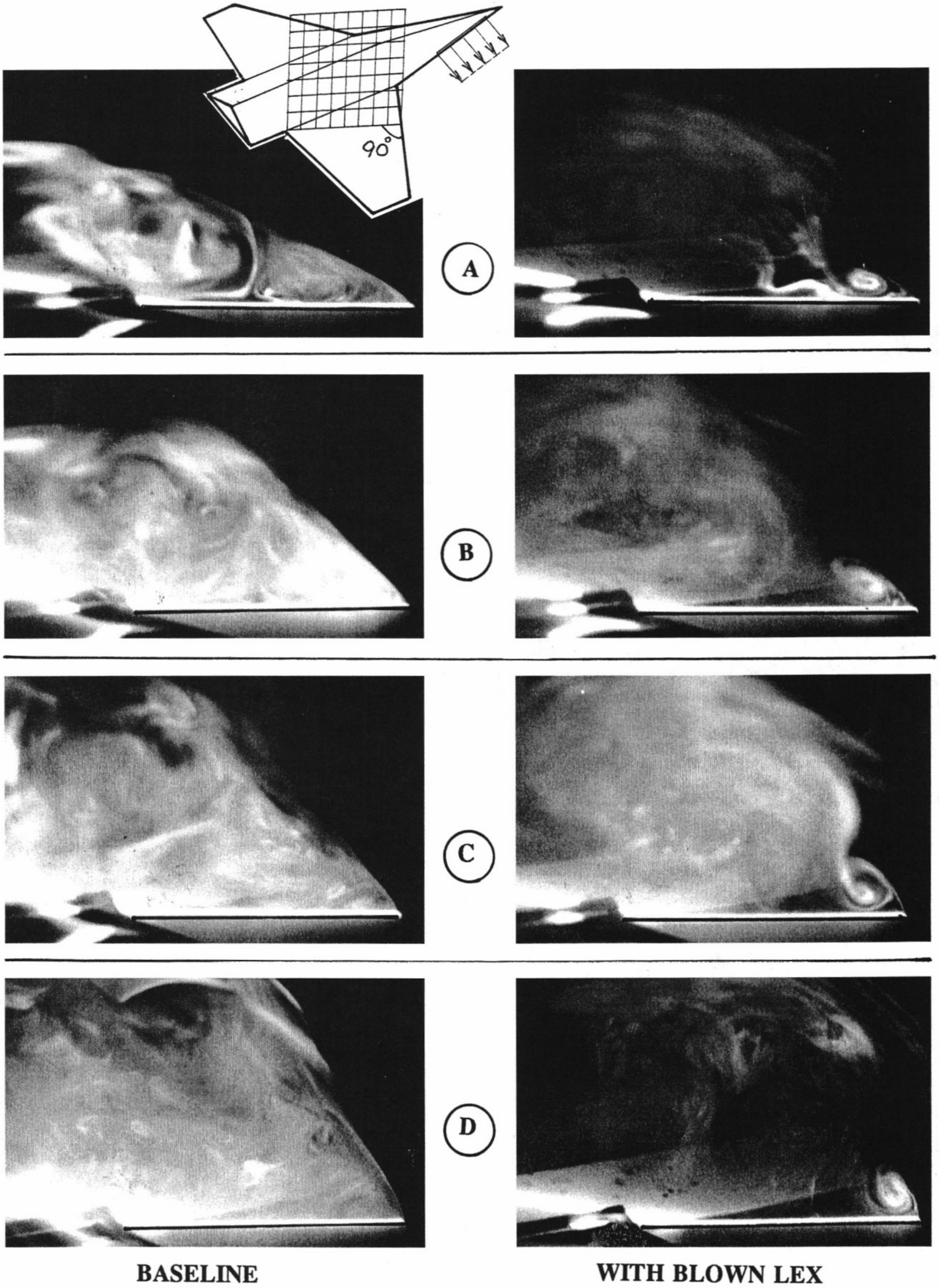


Fig.5 Smoke Visualizations With Right-Front-Half LEX Blowing
A. α=20°; **B.** α=25°; **C.** α=30°; **D.** α=35°

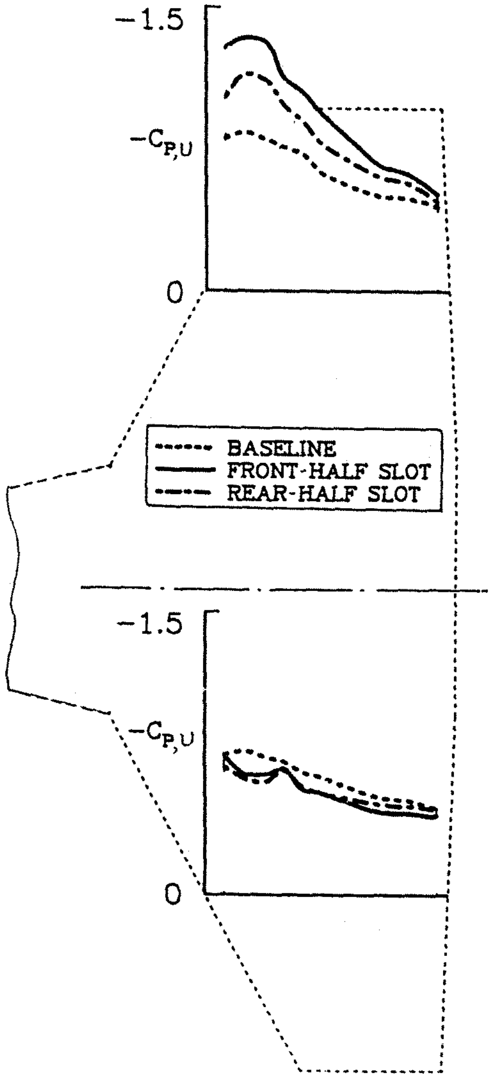


Fig.6 Wing Upper-Surface Pressure Distributions at α=30°

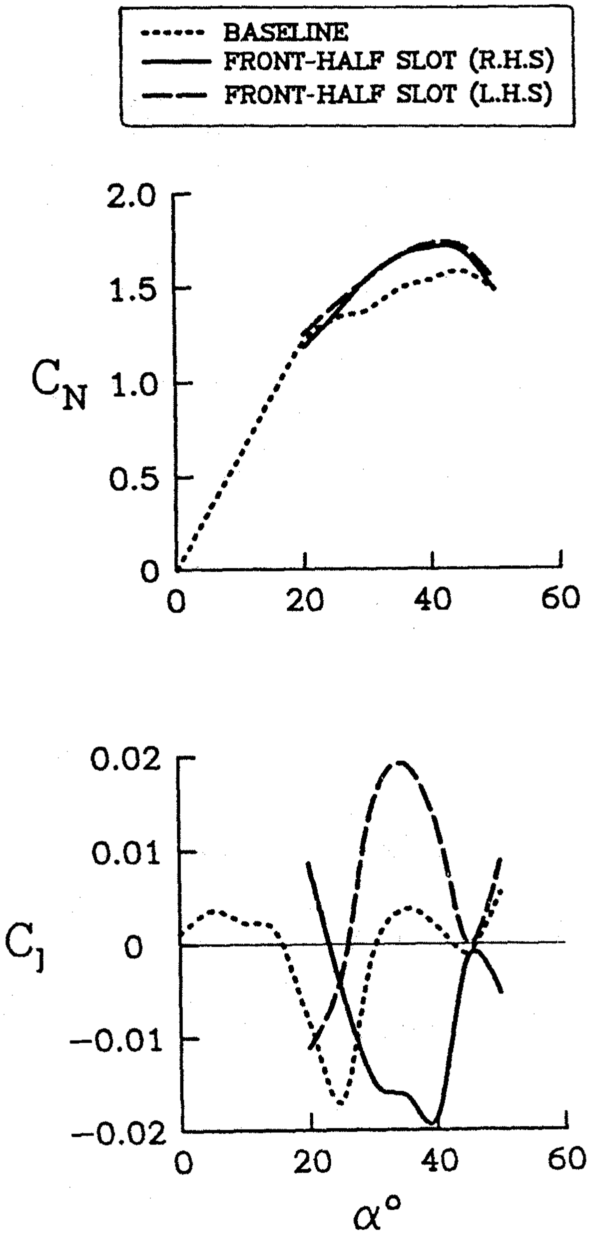


Fig.7 Typical Normal Force and Rolling Moment Characteristics Versus Alpha: Showing LEX Slot Blowing Effects

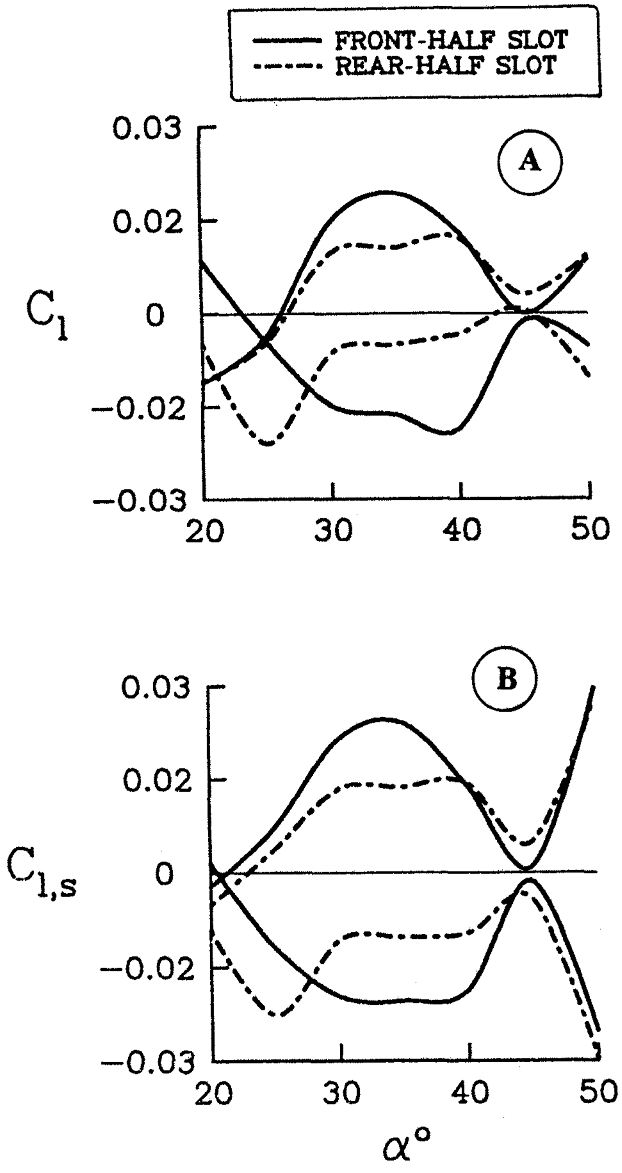


Fig.8 Rolling Moment Comparisons of Front-Half and Rear-Half LEX Slot Blowing:

A. Body-Axis Rolling Moment

B. Stability-Axis Rolling Moment

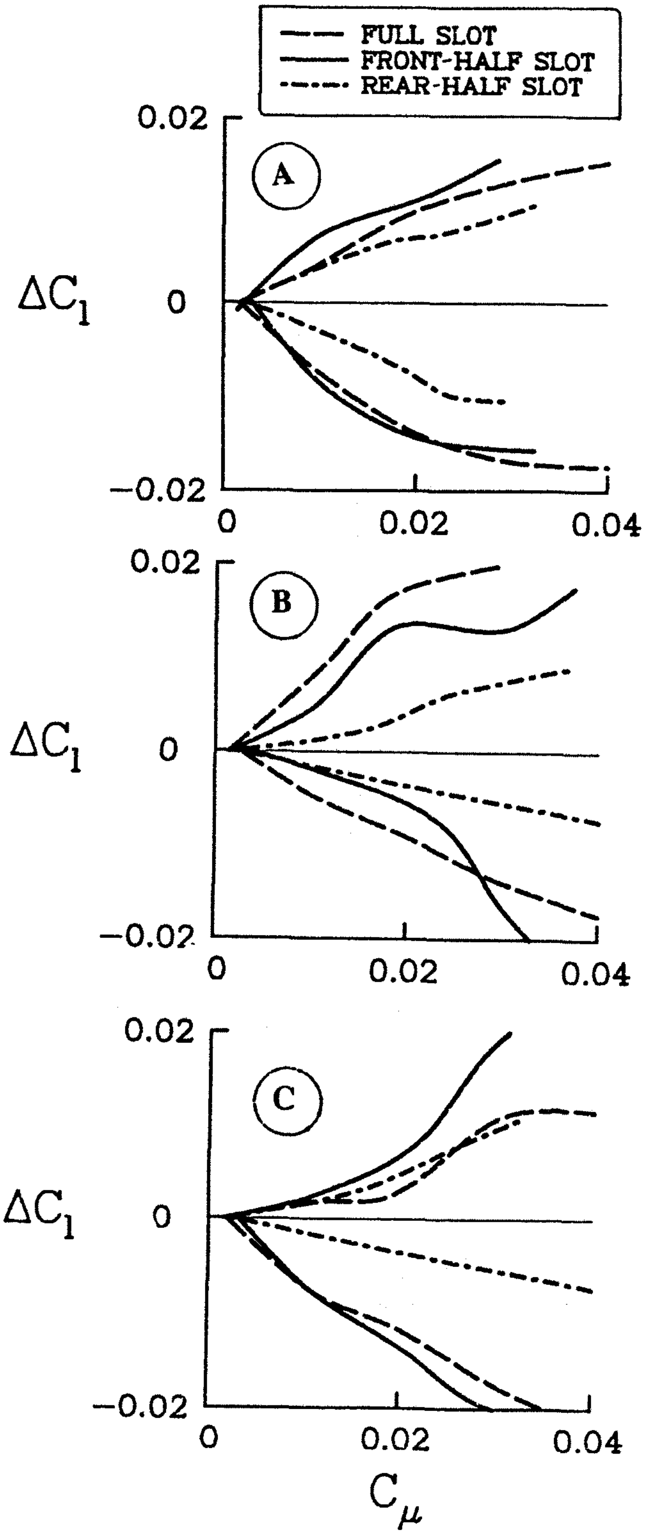


Fig.9 Rolling Moment Versus LEX Momentum Coefficient:

A. α=30°

B. α=35°

C. α=40°

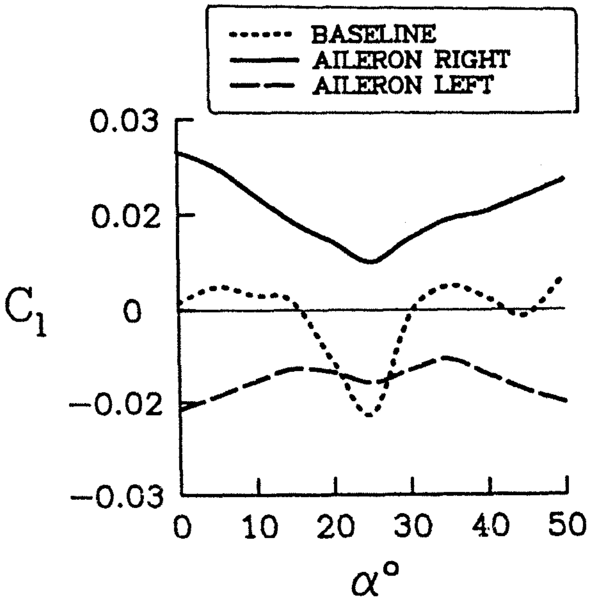


Fig.10 Aileron Rolling Moment

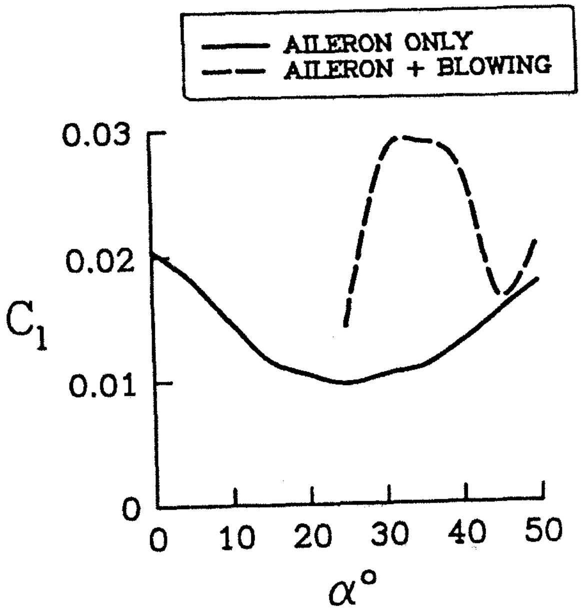


Fig.11 Rolling Moment With Ailerons Plus LEX Blowing