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Aircraft Spoiler Effects Under Wind Shear

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Effects of symmetrical and nonsymmetrical spoiler configurations on an aircraft model under wind shear are experimentally studied. Lift, drag, and side forces in addition to pitching, yawing, and rolling moments are investigated for various angles of attack, sideslip angles, spoiler deflections, and wind shear velocity ratios. The results substantiate that spoiler deflection increases the drastic lift reduction caused by wind shear, especially at low angles of attack. Wind shear also tends to intensify the spoiler effect on the side force and yawing moment, while it affects the resulting rolling moment only at high angles of attack. Spoiler deflections, however, have practically no effect on the aircraft stability margin which normally increases by the presence of wind shear.

Nomenclature

C_D = drag coefficient
C_L = lift coefficient
C_M = pitching moment coefficient, taken about $\frac{1}{4}$ of the wing mean aerodynamic chord, positive for a nose-up aircraft
C_n = yawing moment coefficient, positive for a backward right wing
C_r = rolling moment coefficient, positive for a downward right wing
C_s = side force coefficient
U = freestream velocity
V = wind shear velocity
α = aircraft angle of attack
β = aircraft sideslip angle, positive clockwise direction
δ = spoiler deflection angle

Introduction

ONE of the challenging problems in aviation safety is the effect of wind shear on the aerodynamic characteristics of an aircraft. The most dangerous form of wind shear, referred to as downburst or microburst, occurs close to the ground where the turbulence due to wind shear can be hazardous to the aircraft during takeoff and landing. In the last case, attention is given to the aircraft-spoiler configuration which may considerably affect the aerodynamic characteristics of the aircraft.

The flowfield associated with spoilers is very complex and includes separation, reattachment, and vortex shedding. The interaction between shedding vortices from the spoiler tip and the finite wing vortex system results in a highly turbulent oscillatory wake which affects the spoiler flap system and the effectiveness of the tail control surfaces. No satisfactory theoretical methods are available to predict this complex flow configuration, and designers depend on wind-tunnel experiments to assist spoiler control characteristics.[1] A survey of available mathematical models[2] shows that existing models cover only the case of two-dimensional airfoils with deflected spoilers.[3-5] Investigations on finite wings fitted with spoilers and on the interaction between the complete aircraft and the spoiler system seem to be beyond the capabilities of existing computational methods.

Studies on wind shear hazards can be traced back to the late seventies. At this stage, studies were oriented to wind shear detection systems to help avoid encountering dangerous situations of downcoming burst.[6] The vast data base for weather conditions related to wind shear established by the Joint Airport Weather Studies (JAWS) project office gave rise to several wind shear spatial models.[7-10] There had also been some efforts devoted to reducing wind shear hazards through flight path optimization[11,12] and improvement of aircraft control system robustness.[13] It is clear that while so much attention was paid over these two decades to understand the physics of microburst flowfield, and consequently, the measures required to avoid encountering a downcoming burst, relatively little seems to have been achieved in the investigation of the aerodynamic loads applied to an aircraft subjected to hazardous wind shear conditions.

Tests were carried out by some authors to study, separately, the effect of spoilers[14-17] and wind shear flow[18,19] on the aerodynamic characteristics of airfoils, wings and complete aircraft models. However, the study of the spoilers in the presence of wind shear has received relatively less attention. In the present work, the aerodynamic loads on an aircraft/spoiler configuration subject to downcoming burst are experimentally investigated. The longitudinal and lateral aerodynamic forces and moments are measured at different wind shear velocities and various spoiler deflections.

Experimental Setup

The experiments were performed in a nonreturn blowdown low-speed wind tunnel. The test section is 0.7 m wide, 0.5 m high, and 2.0 m long. The flow representing downdraft was obtained from a fan-duct arrangement. Uniform supply of air, representing downdraft, was maintained by having air pass through a settling chamber with three levels of screens inside it. The chamber was placed right on top of the test section. A survey of the downcoming air flowfield verified that the downcoming burst velocity V was uniform.

A scaled-down model of B-747 airplane, of 0.586-m fuselage length, and 0.505-m wing span with sweep back, was employed in the investigation. The wing has a basic NACA 23012 airfoil section with an aspect ratio of 6.64 and a taper ratio of 0.267. The wing tip, root, and mean aerodynamic chords are 0.032, 0.12, and 0.085 m, respectively. The sweepback angle at the quarter chord length is 40 deg and the wing area is 0.038 m^2. The horizontal tail has a basic NACA 0010 airfoil section with 7.2-cm root chord, 1.8-cm tip chord, and 19.2-cm span. The vertical stabilizer is of 2.8-cm top chord, 10.4-cm bottom chord, and 8.6-cm height.

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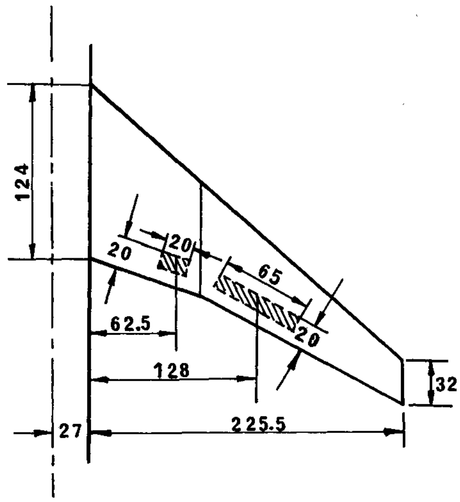

Fig. 1 Top view of the aircraft wing model showing spoiler locations.

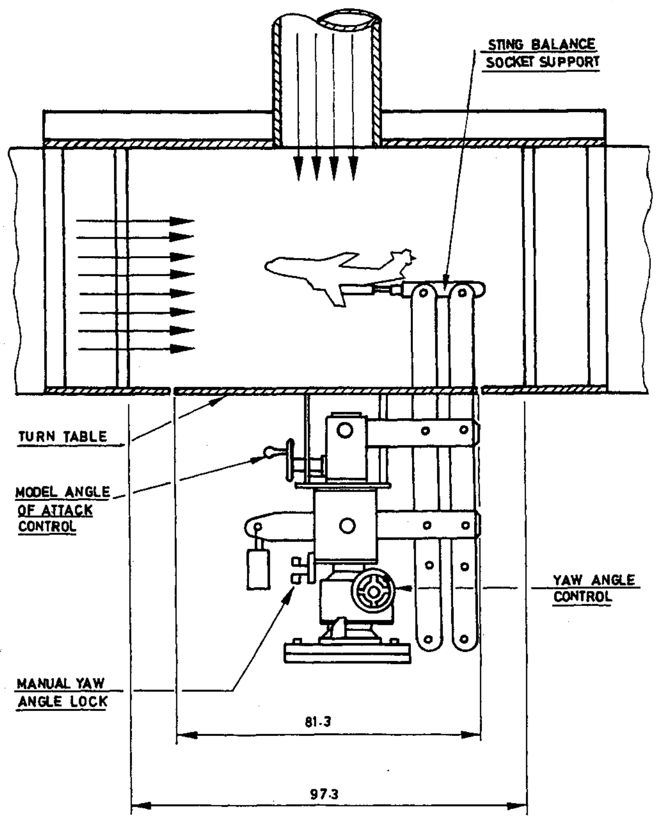

Fig. 2 Schematic of model mounting in wind-tunnel test section.

Flight and inboard spoilers were used for various symmetrical and nonsymmetrical configurations. The spoilers used were flat plates inclined to the wing surface at specific deflections, and were hinged at 0.02 m from the wing trailing edge as shown in Fig. 1. The flight and inboard spoilers have chord lengths of 8.82 and 14.1% of the mean aerodynamic chord, and span lengths of 12.8 and 4% of the wing span, respectively. The arrangement for the spoilers are as follows: case 1) aircraft with flight spoiler on right wing side; case 2) aircraft with flight and inboard spoilers on right wing side; case 3) aircraft with flight spoiler on both wing sides; and case 4) aircraft with flight and inboard spoilers on both wing sides.

Forces and moments experienced by the aircraft model were measured by a strain gauge six components sting balance as illustrated in Fig. 2. Measurement readings were taken to an HP-85 data acquisition system.

Results and Discussion

All results were obtained at freestream velocity of 20 m/s, corresponding to $Re = 1.2 \times 10^5$ based on the mean aerodynamic chord. The velocity of the downcoming flow is varied from 0 to 10 m/s through a duct flow area of 500 cm^2. The angle of attack is changed from 0 to 16 deg at steps of 2 deg. The sideslip angle is varied from 0 to 16 deg at steps of 2 deg in a direction such that the port wing leads the starboard wing. The spoiler deflections are taken to be 15, 30, 45, and 90 deg. When the results were plotted incorporating so many values of the variables, the figures got extremely congested. Therefore, the curves are plotted for just the following variables: 1) wind shear velocity ratio $V/U = 0.1$ and 0.5; 2) spoiler deflection angle $\delta = 15$ and 90 deg; 3) sideslip angle $\beta = 0$ and 8 deg; and 4) angle of attack $\alpha = 4$ and 16 deg.

All figures presented next are made up of the four cases of spoiler configurations specified in the previous section. The results are summarized in two groups of figures: 1) longitudinal aerodynamic characteristics (C_L, C_D, and C_M): presented in two sets of figures; one at $\beta = 0$ deg and the other at $\beta = 8$ deg; and 2) lateral aerodynamic characteristics (C_s, C_n, and C_r): presented in two sets of figures; one at $\alpha = 4$ deg and the other at $\alpha = 16$ deg.

In order to appreciate the intensity of the problem, the baseline, i.e., for no wind shear ($V/U = 0$) and undeflected spoilers ($\delta = 0$ deg), is plotted in all applicable cases, i.e., Figs. 3–8.

Lift Coefficient

Figures 3 and 4 exhibit the great losses of lift on aircraft subjected to wind shear. These losses superimpose the reduction caused by spoiler deflection. The greatest loss of lift is experienced at low angles of attack; the maximum being at $\alpha = 4$ deg, and the minimum being at the highest angle of attack investigated ($\alpha = 16$ deg). It seems that near stall the

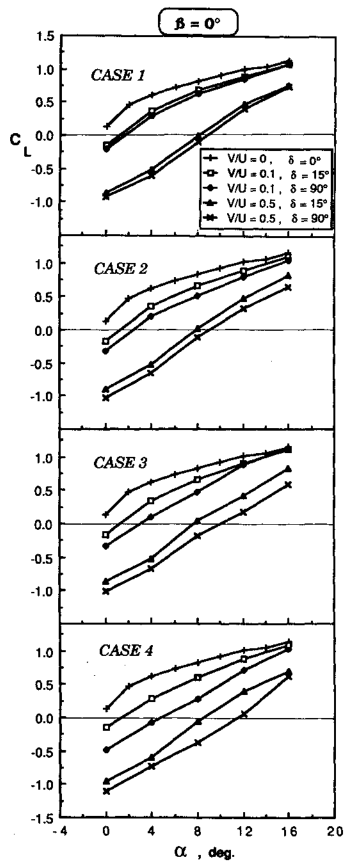

Fig. 3 Effect of wind shear and spoiler deflection on lift coefficient ($\beta = 0$ deg).

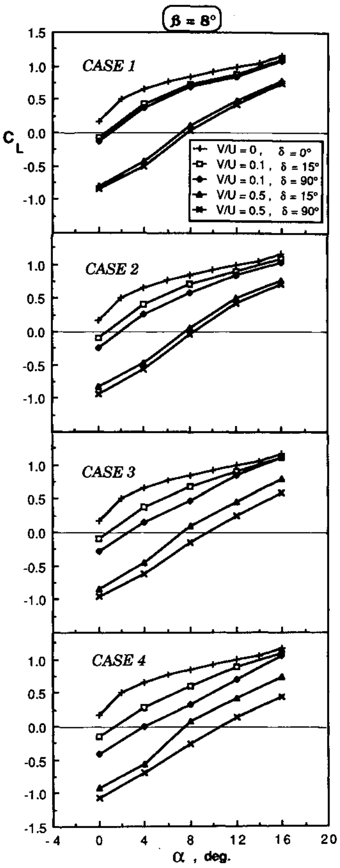

Fig. 4 Effect of wind shear and spoiler deflection on lift coefficient (β = 8 deg).

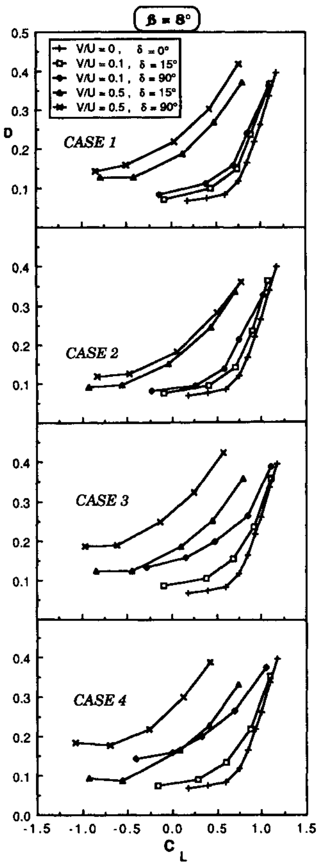

Fig. 6 Drag polar under wind shear and spoiler deflection effects (β = 8 deg).

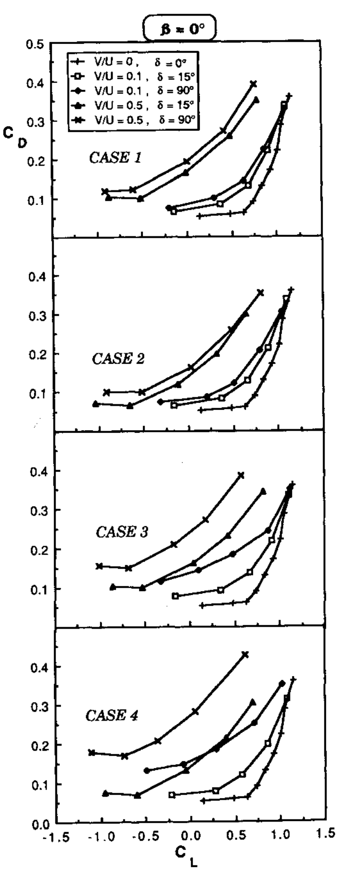

Fig. 5 Drag polar under wind shear and spoiler deflection effects (β = 0 deg).

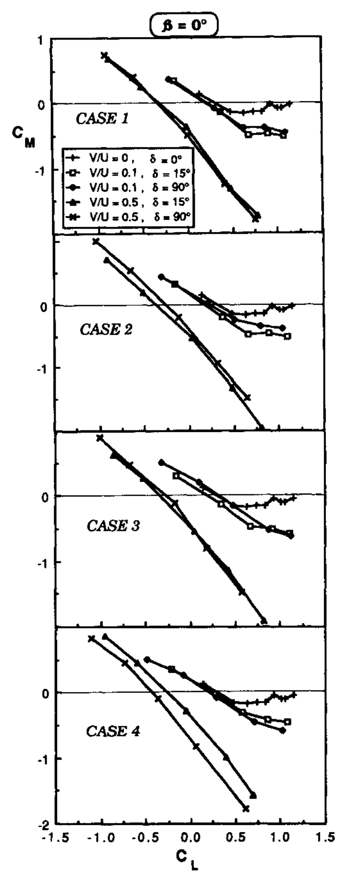

Fig. 7 Pitching moment-lift variations (β = 0 deg).

wing separation (occurring upstream of the spoiler position) over-rides the spoiler effect. Therefore, at high angles of attack and low-wind shear velocity ratio, the lift reduction due to spoilers is negligible.

As the spoiler angle and the wind shear velocity ratio increase, the zero lift angle of attack moves towards higher values (up to 12 deg in some cases) and the lift curve slope increases slightly. Comparing the two figures indicates that the sideslip angles up to 8 deg have negligible effect on the lift coefficient.

Tables 1 and 2 illustrate the order of magnitude of changes in lift, drag, and pitching moment for symmetrical and nonsymmetrical deflections of flight spoiler at zero sideslip angles. For the symmetrical configuration at 15-deg spoiler angle, the percentage reduction of lift, due to increase of wind shear

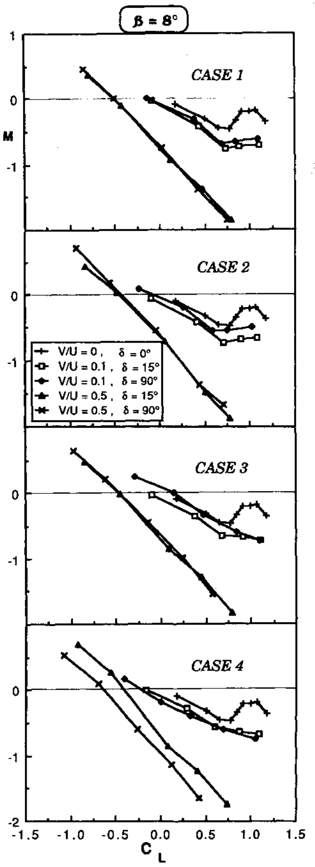

Fig. 8 Pitching moment-lift variations (β = 8 deg).

velocity ratio from 0.1 to 0.5, is about 250 and 25% for angles of attack of 4 and 16 deg, respectively. For the case of V/U = 0.1, as the spoiler angle increases from 15 to 90 deg, this percentage in lift reduction becomes around 70 and 1% for angles of attack of 4 and 16 deg, respectively. This alarming observation in the role of the angle of attack in reducing the potential threat leads to the obvious solution that when wind shear is encountered the pilot has to increase the angle of attack.[18,19]

Drag Coefficient

Figures 5 and 6 reveal that when spoilers are placed on one side (cases 1 and 2) the effect on the drag polar is mainly due to wind shear. On the other hand, when spoilers are used more extensively (cases 3 and 4) wind shear becomes less dominant on the drag polar. For constant lift values, the drag force increases drastically as the wind shear velocity ratio increases, while for symmetrical spoiler arrangements the drag increase due to spoilers is more profound. Nevertheless, for a fixed angle of attack, the effect of V/U on the drag coefficient is very small, as revealed in Table 1.

Increasing wind shear under the same spoiler deflection shifts the drag polar towards lower lift values associated with slight drag increase. On the other hand, the effect of spoiler deflection is to shift the drag polar in such a way that the drag force coefficient assumes higher values. This spoiler effect increases as the wind shear velocity increases.

It is clearly indicated in Table 2 that the spoiler effect is more experienced at low angles of attack. For example, in the case of flight spoilers on both wing sides, increasing spoiler deflection from 15 to 90 deg at an angle of attack of 4 deg and V/U = 0.1 causes an increase of C_D 11 times its increase at an angle of attack of 16 deg. As previously mentioned, this effect is attributed to the fact that wing separation over-rides the spoiler action.

Pitching Moment Coefficient

It is observed from Figs. 7 and 8 that the major effect on the equilibrium point and the stability margin arises from wind shear contribution. This contribution improves the stability margin, before stall, for symmetric and nonsymmetric spoiler configurations, by decreasing the lift coefficient and adding a smaller positive (nose-up) pitching moment such that the C_M-C_L curve is shifted towards lower C_L values. It also displaces the equilibrium point towards negative lift coefficients. Additionally, the slope of C_M-C_L curves becomes more negative as V/U increases. The figures also reveal that the spoiler angle has practically no contribution on the stability margin. This is in line with the results reported in Ref. 2.

The figures demonstrate that spoilers add a small nose-up pitching moment. The rate at which this pitching moment is

Table 1 Percent variations of C_L, C_D, and C_M caused by increasing V/U from 0.1 to 0.5, at δ = 15 deg and β = 0 deg

	Percent C_L		Percent C_D		Percent C_M	
Angle of attack	4	16	4	16	4	16
Flight spoiler on right wing	−240	−29	+17	+4	+276	−234
Flight spoiler on both wings	−254	−25	+8	+3	+300	−230

Table 2 Percent variations of C_L, C_D, and C_M caused by increasing δ from 5 to 90 deg, at V/U = 0.1 and β = 0 deg

	Percent C_L		Percent C_D		Percent C_M	
Angle of attack	4	16	4	16	4	16
Flight spoiler on right wing	−18	−1	+16	+2	+34	+10
Flight spoiler on both wings	−70	−1	+55	+5	+260	+1

added per spoiler deflection decreases when the angle of attack increases.[2] This is confirmed in Table 2; as the flight spoiler deflection symmetrically increases from 15 to 90 deg, at α = 4 deg, V/U = 0.1 and zero sideslip, the pitching moment coefficient increases by 260% of its initial value.

Table 1 demonstrates that as V/U is increased from 0.1 to 0.5, at δ = 15 deg, the percentage change in the pitching moment coefficient becomes 300 and −230% for 4- and 16-deg angles of attack, respectively. This indicates that low angles of attack contribute a nose-up pitching moment, while a nose-down pitching moment is added at high angles of attack. This phenomenon is attributed to the interaction between the wind shear flow and the wing flow separation. The effect of high wind shear velocity ratio is to reattach the separated flow at high angles of attack as remarked earlier when discussing the lift coefficient.

Side Force Coefficient

Figures 9 and 10 elucidate the variations of C_s against the wind shear velocity ratio V/U. It is noticed that for nonsymmetrical spoiler configurations (cases 1 and 2), the spoiler deflection has a slight effect on the side force, especially at high sideslip angles where the right side spoiler is situated in the wake of the fuselage. On the other hand, for symmetrical spoiler configurations (cases 3 and 4), the effect of the spoiler deflection is to increase the side force coefficient.

As anticipated, the figures show a remarkable increase in the side force contributed by fuselage and vertical tail as the sideslip angle is increased. For all cases under consideration it is evident that at high angles of attack the side force coefficient assumes higher values for both symmetrical and nonsymmetrical spoiler configurations.

Yawing Moment Coefficient

The variation of yawing moment with wind shear is presented in Figs. 11 and 12. The main contributions to C_n are

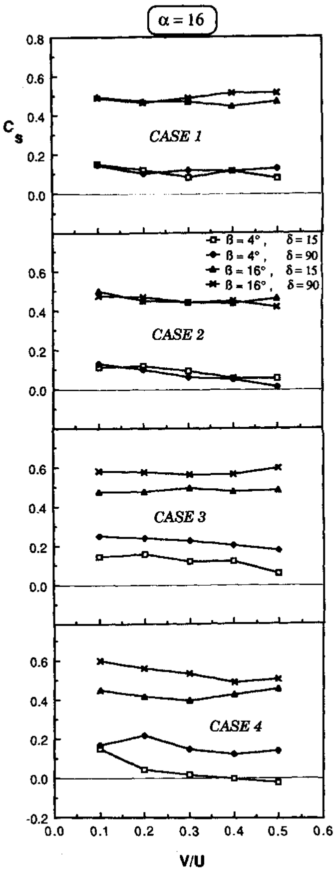

Fig. 10 Contributions of sideslip and spoiler deflection to side force variations with wind shear (α = 16 deg).

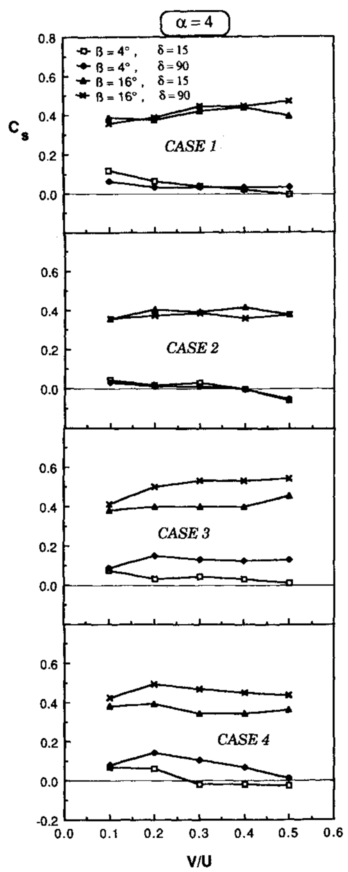

Fig. 9 Contributions of sideslip and spoiler deflection to side force variations with wind shear (α = 4 deg).

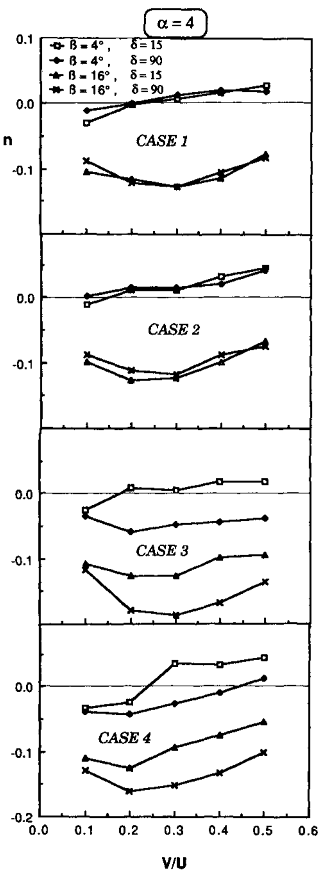

Fig. 11 Variations of the yawing moment coefficient (α = 4 deg).

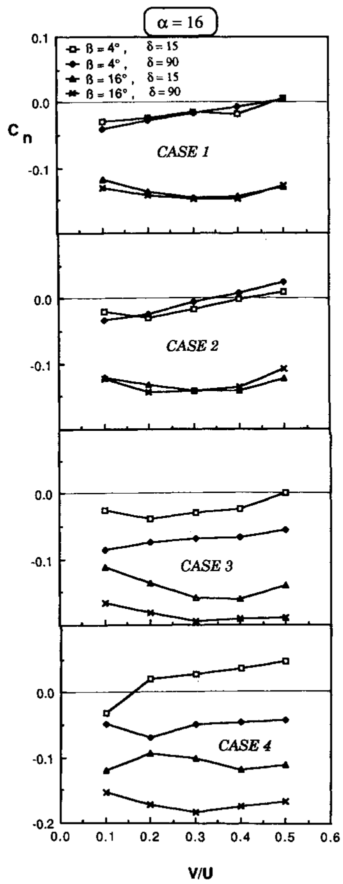

Fig. 12 Variations of the yawing moment coefficient (α = 16 deg).

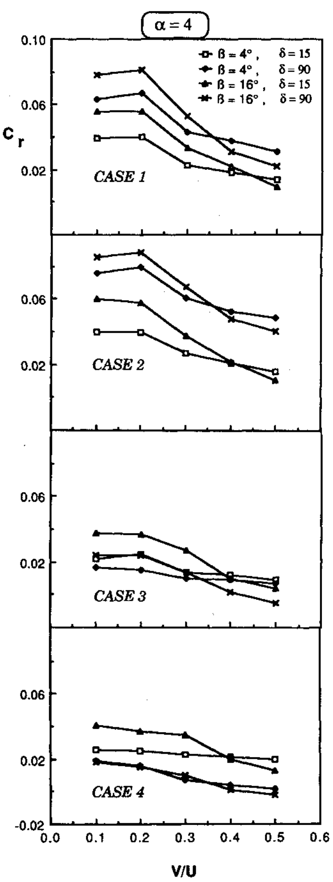

Fig. 13 Rolling moment coefficient of the aircraft model (α = 4 deg).

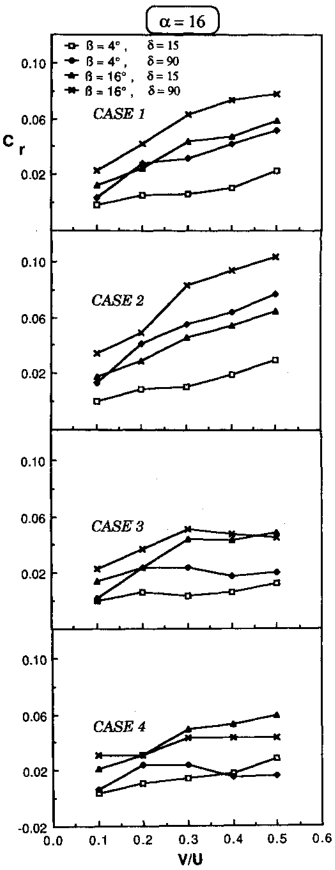

Fig. 14 Rolling moment coefficient of the aircraft model (α = 16 deg).

observed to arise from fuselage, vertical tail, and lateral control elements. For symmetrical spoiler deflections, a negative (anticlockwise) yawing moment is added. In this configuration the drag increases on the leading wing half (port wing) and gets higher than the drag on the starboard wing (imbedded in the wake of the fuselage). This contribution becomes less important when the right spoiler is deflected alone, e.g., when right wing spoilers are deflected alone (cases 1 and 2), the effect on the yawing moment is found to be weak.

In addition, the figures reveal that higher sideslip angles are accompanied by higher negative yawing moment; which is in line with the observation mentioned in the previous section. Comparing Figs. 11 and 12 indicates that for high angles of attack the yawing moment coefficient assumes more negative values for both symmetrical and nonsymmetrical configurations.

Rolling Moment Coefficient

Figures 13 and 14 demonstrate an interesting behavior of the rolling moment as a function of wind shear at low and high angles of attack. This difference is mainly manifested at nonsymmetric spoiler configurations (cases 1 and 2). While the wind shear tends to decrease the rolling moment coefficient at low angles of attack, the curves assume an increasing trend at high angles of attack. This phenomenon is attributed to the interaction of wind shear with the flow separation at high angles of attack where the downdraft tends to reattach the separated flow.

The figures also illustrate that for right spoiler deflections (cases 1 and 2) the rate at which this rolling moment is added per spoiler deflection angle remains constant—or even decreases—at low angles of attack, while for high angles of attack it increases. This indicates that the spoiler effectiveness for roll control increases at high angles of attack under wind shear exposure. Since it is generally recommended to increase the aircraft angle of attack under wind shear—even beyond classical stall limits—in order to partially compensate for the lift loss,[18,19] it is expected that the spoiler roll control effectiveness increases in such conditions.

At low angles of attack, as the sideslip angle increases, up to $V/U = 0.3$, an additive positive rolling moment is generated; and it is observed more at low spoiler deflections. This effect is reversed at high wind shears. On the other hand, at high angles of attack increasing the sideslip angle adds a positive rolling moment for all wind shear velocity ratios, and this rate of increase becomes more pronounced as the downdraft increases.

Finally, it is concluded from this study that the flow configuration is very complex and more detailed flow studies are required to assist better understanding of the problem. For example, the effect of banking angle needs further studies to cover all aspects of flight conditions.

Conclusions

The aerodynamic forces and moments on an aircraft model integrated with different spoiler configurations have been measured under the effect of a downcoming wind shear flow. The results reveal the following main conclusions:

1) Spoiler deflection increases the already experienced loss of lift caused by wind shear, especially at low angles of attack. At high angles of attack and low wind shear the effect of spoiler deflection is less pronounced.

2) Wind shear tends to shift the drag polar towards lower lift values. Although the corresponding minimum drag increase is slight, it becomes more important with spoiler deflection.

3) Spoiler deflection has practically no effect on the aircraft stability margin. Nevertheless, the stability margin increases by the presence of downcoming wind shear.

4) In the presence of sideslip, the effect of symmetric deflection of spoilers is to produce a positive side force and a negative yawing moment. For high wind shear velocity ratios these effects are intensified.

5) Spoiler effectiveness for roll control increases at high angles of attack under wind shear exposure.

6) Increasing the angle of attack under downburst conditions leads to a) compensation of lift loss; b) increasing the side force; c) positive (increase) of the rolling moment; and d) reversed tendency of the rolling moment as a function of the burst velocity from a decreasing to an increasing attitude.

7) In general, the spoiler effect is more profound when spoilers are used extensively.

References

[1]Bodapati, S., Mack, M. D., and Karamcheti, K., "Basic Studies of the Flow Fields of Airfoil-Flap-Spoiler System," AIAA Paper 82-0173, Jan. 1982.

[2]Al-Bahi, A. M., and Ghazi, M. A., "An Experimental Investigation on Spoiler Effects," AIAA Paper 91-3214, Sept. 1991.

[3]Pfeiffer, N. J., and Zumwalt, G. W., "Computational Model for Low Speed Flow Past Airfoils with Spoilers," *AIAA Journal*, Vol. 20, No. 3, 1982, pp. 376–382.

[4]Lee, C. S., and Bodapati, S., "Calculation of the Unsteady Flow Field of an Airfoil with a Deflected Spoiler by Vortex Method," Joint Inst. for Aeronautics and Acoustics, Tr-62, Stanford Univ., Stanford, CA, 1985.

[5]Tou, H. B., and Hancock, G. J., "Inviscid Theory of Two-Dimensional Aerofoil/Spoiler Configuration at Low Speed," *Aeronautical Journal*, Vol. 91, Oct. 1987, pp. 350–366.

[6]Greene, R. A., "Airborne Detection of Low-Level Wind Shear (Wind Shear Monitor System)," *Journal of Aircraft*, Vol. 16, No. 12, 1979, pp. 823–827.

[7]Campbell, C. W., and Sanborn, V. A., "Spatial Model of Wind Shear and Turbulence," *Journal of Aircraft*, Vol. 21, No. 12, 1984, pp. 929–935.

[8]Ivan, M., "A Ring-Vortex Downburst Model for Flight Simulations," *Journal of Aircraft*, Vol. 23, No. 3, 1986, pp. 232–236.

[9]Schultz, T. A., "A Multiple Vortex Ring Model of the DFW Microburst," *Journal of Aircraft*, Vol. 27, No. 2, 1990, pp. 163–168.

[10]Vicroy, D. D., "A Simple, Analytical, Axisymmetric Microburst Model for Downdraft Estimation," NASA TM-104053, DOT/FAA/RD-91/10, Feb. 1991.

[11]Psiaki, M. L., and Stengel, R. F., "Optimal Flight Paths Through Microburst Wind Profiles," *Journal of Aircraft*, Vol. 23, No. 8, 1986, pp. 629–635.

[12]Campos, L. M. B. C., "On a Pitch Control Law for a Constant Glide Slope Through Windshears," *Aeronautical Journal*, Vol. 93, Oct. 1989, pp. 290–300.

[13]Kim, B. K., and Bassi, J. A., "Wind Shear Estimation by Frequency-Shaped Optimal Estimator," *Journal of Guidance, Control, and Dynamics*, Vol. 9, No. 2, 1986, pp. 164–168.

[14]Wentz, W. H., Ostowari, C., and Seetharam, H. C., "Effects of Design Variables on Spoiler Control Effectiveness, Hinge Moments and Wake Turbulence," AIAA Paper 81-0072, Jan. 1981.

[15]McLachlan, B. G., Karamcheti, K., Ayoub, A., and Hadjidaskis, G., "A Study of the Unsteady Flow Field of an Airfoil with Deflected Spoiler," AIAA Paper 83-2131, Aug. 1983.

[16]Lee, C. S., and Bodapati, S., "Experimental Investigation of the Flow Field of an Airfoil with Spoilers," *AIAA Journal*, Vol. 25, No. 11, 1987, pp. 1411–1416.

[17]Lee, C. S., Bodapati, S., and Karamcheti, K., "Flow Measurements of an Airflow with Deflected Spoilers," AIAA Paper 83-0365, Jan. 1983.

[18]Aly, M., Olwi, I., Al-Bahi, A., and Ghazi, M., "Experimental Investigation of the Wind Shear Effect on the Aerodynamic Forces on a Wing," AIAA Paper 91-3216, Sept. 1991.

[19]Olwi, I., Aly, M., Ghazi, M., and Al-Bahi, A., "A Study of Aerodynamic Forces and Pitching Moment on an Aircraft Model Subject to Wind Shear," *Proceedings of the 3rd Saudi Engineering Conference*, Riyadh, Saudi Arabia, Nov. 1991, pp. 438–442.