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Reduction of Transient Adverse Effects of Spoilers

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A method is proposed to reduce the adverse lift and moment induced on an airfoil during the rapid deployment of its spoiler. The idea is to introduce a gap between the airfoil surface and the extended spoiler such that the flow through the base-vented spoiler abates the effects of the starting vortex shed from the spoiler tip. Results from an experimental study, which is carried out to demonstrate the effectiveness of the idea, substantiate that the magnitudes of adverse lift and moment decrease with increasing gap size. In addition, variations of the angular speed, deflection of the spoiler, and the angle of attack may also influence the adverse effects.

Nomenclature

C_d = sectional drag coefficient
C_l = sectional lift coefficient
C_{la} = coefficient of maximum adverse lift
C_m = sectional pitching moment coefficient about one-quarter chord
C_{ma} = coefficient of maximum adverse moment
c = airfoil chord
G_h = gap size of spoiler
h = spoiler height
T = spoiler opening time
t = time
t_a = aerodynamic delay
U = freestream speed
α = angle of attack of airfoil
θ = spoiler deflection
ω = angular speed of spoiler, θ/T

Introduction

A SPOILER is a control surface that is designed to spoil the attached flow over the upper surface of a wing and thus reduce the lift. When deployed, the spoiler also creates a low-pressure region downstream such that the drag is substantially increased. As a result, it is widely used during aircraft landing.

A renewed interest in spoilers as an active control device has led to some recent research[1,2] on the understanding of associated unsteady aerodynamic characteristics. For example, based on the measurements of the reversed flow downstream of a moving spoiler, vorticity transport is found to be convective.[3] A further investigation of the flow state behind the spoiler helps establish criteria as flow-state identifiers in the active control of unsteady separated flows.[4] In the view of aviation safety, spoiler effects may be affected by wind shear.[5] Although the adverse effects in lift and moment have been known for some time,[1,2] little work has been carried out to identify ways of reducing these undesirable features. The purpose of the present study is to investigate how the adverse lift and moment are influenced if base-venting is introduced.

When a spoiler is suddenly extended at a high rotational speed, the flow over the upper surface of the wing separates from the spoiler tip because of surface discontinuity. Because of the intensive shear flow near the tip, the resulting shear layer rolls up to form a strong starting vortex[6] behind the spoiler (Fig. 1a). This starting vortex induces an initial increase in lift and a decrease in pitching moment; this is usually referred to as adverse lift and moment, respectively. Once the spoiler reaches its maximum deflection, the vortex stops growing and detaches from the spoiler tip to convect downstream, as identified by flow visualization.[3,4] As the vortex moves farther downstream, the lift will decrease and eventually attain its steady-state value. If the spoiler remains extended, flow continues to separate from its tip and interacts with another shear layer emanating from the trailing edge of the airfoil such that periodic vortex shedding in the wake occurs.

Although short in duration, the adverse lift effect may be significant, even in the case of a moderate rate of spoiler rotation, e.g., 312 deg/s (Ref. 2). It can be as large as 50% of the net change in lift, and the magnitude of the adverse moment may be equal to the net change in moment.[1] Therefore, they may affect the aircraft during landing. A method is proposed to reduce this initial increase in lift by creating another starting vortex whose sense of rotation is opposite to the former one (Fig. 1b). This can be achieved by simply introducing a gap between the spoiler and the wing such that a counter-rotating vortex pair is shed from the upper and lower tips of the spoiler. (To avoid seriously affecting the drag, the spoiler height is preferably kept unchanged when the gap is added.) Therefore, the initial increase in lift on the airfoil will diminish because of the reduction in net circulation of the vortex pair. Certainly, a gap of small size may inhibit vortex formation because of relatively weak shear flow at the lower tip of the spoiler and render this method ineffective. If the gap size is very large, the effectiveness of the spoiler in terms of destroying the lift will be seriously affected. As a result, an experimental study is needed to identify the influence of base-venting on the adverse effects.

Experimental Setup

The experiments were performed on a low-speed wind tunnel of the closed-circuit type. A NACA 0012 airfoil with chord length c = 0.4 m and 0.8 m span was mounted vertically in the test section, which is 1.2 m wide, 0.8 m high, and 3 m long, as shown in Fig. 2. Small clearances of a maximum of 2 mm at the top and bottom ends of the airfoil were allowed to avoid any wall interference. The airfoil was supported by a shaft passing through its aerodynamic center, which is one-quarter chord length from the leading edge of the airfoil. A spoiler of height equal to 10% chord was located at 70% chord position from the leading edge of the airfoil. The maximum blockage ratio of the extended spoiler was about 5%, small enough to be neglected in all measurements. This spoiler, which was separated from the airfoil but supported by the

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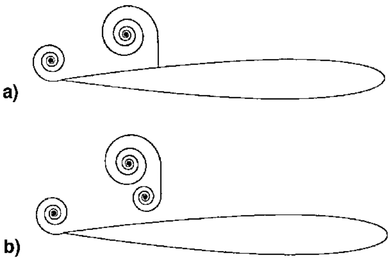

Fig. 1 Flow around airfoil with rapidly deployed spoiler: a) conventional and b) base-vented.

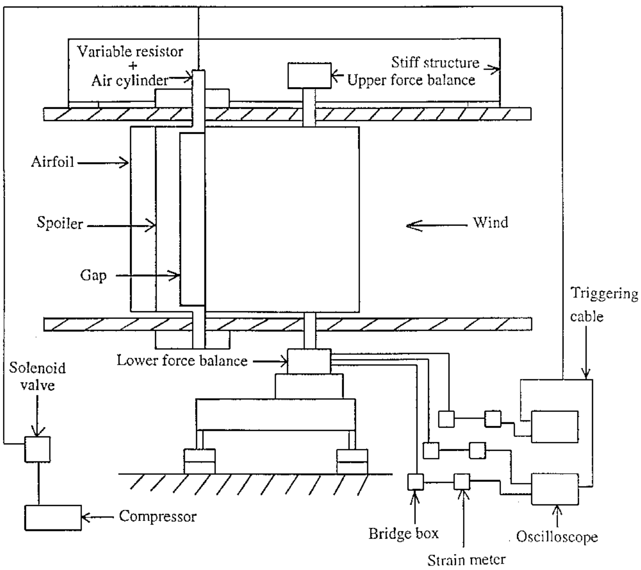

Fig. 2 Schematic of airfoil mounting in wind-tunnel test section.

wind-tunnel walls, was free to rotate from its flush-mounted position to its final deflection θ by activating a pneumatic cylinder placed on the wind-tunnel ceiling outside the test section. Only with this arrangement could the aerodynamic lift and pitching moment on the airfoil be measured without being affected by the actuation force from the air cylinder as would have been the case if it had been placed inside the airfoil. A variable resistor was connected to the stroke of the air cylinder such that its change of voltage reflected the actuation of the spoiler. The opening speed of the spoiler was controlled by a solenoid valve connecting the air cylinder and a portable compressor. Direct current power supplies were required to supply voltages separately to the valve and the variable resistor.

To facilitate two-dimensional force and moment measurements, two identical three-component strain-gauge force balances were attached to the upper and lower ends of the shaft. The upper balance was in turn mounted onto a stiff structure placed on the wind-tunnel ceiling; whereas the lower balance was secured to an indexing table sitting on a platform. The airfoil was allowed to change its angle of attack through this indexing table. Thick rubber pads were placed between the upper structure and the tunnel ceiling, and between the platform and the floor, to avoid any vibration transmitted to the force balances from the tunnel walls and ground. A data acquisition system consisting of three DA-32D dynamic strain meters together with their bridge-boxes and two Nicolet 310 oscilloscopes was connected to the lower force balance for data collection. The upper force balance is not for measurements, but serves to restrict the upper end of the airfoil from having any unnecessary motion when the spoiler is deployed and thus provides symmetric end-conditions on the airfoil. The transient signals of forces and pitching moment, after being amplified and filtered by the strain meters, and the variation of voltage across the resistor, could be displayed on the scopes and stored on diskettes through built-in recorders. Data processing was performed by utilizing the Nicolet and MATLAB software.

Results

All experimental results were obtained at $U = 12$ m/s, which corresponded to a Reynolds number of 3.5×10^5 based on the airfoil chord. Results of some preliminary tests showed that

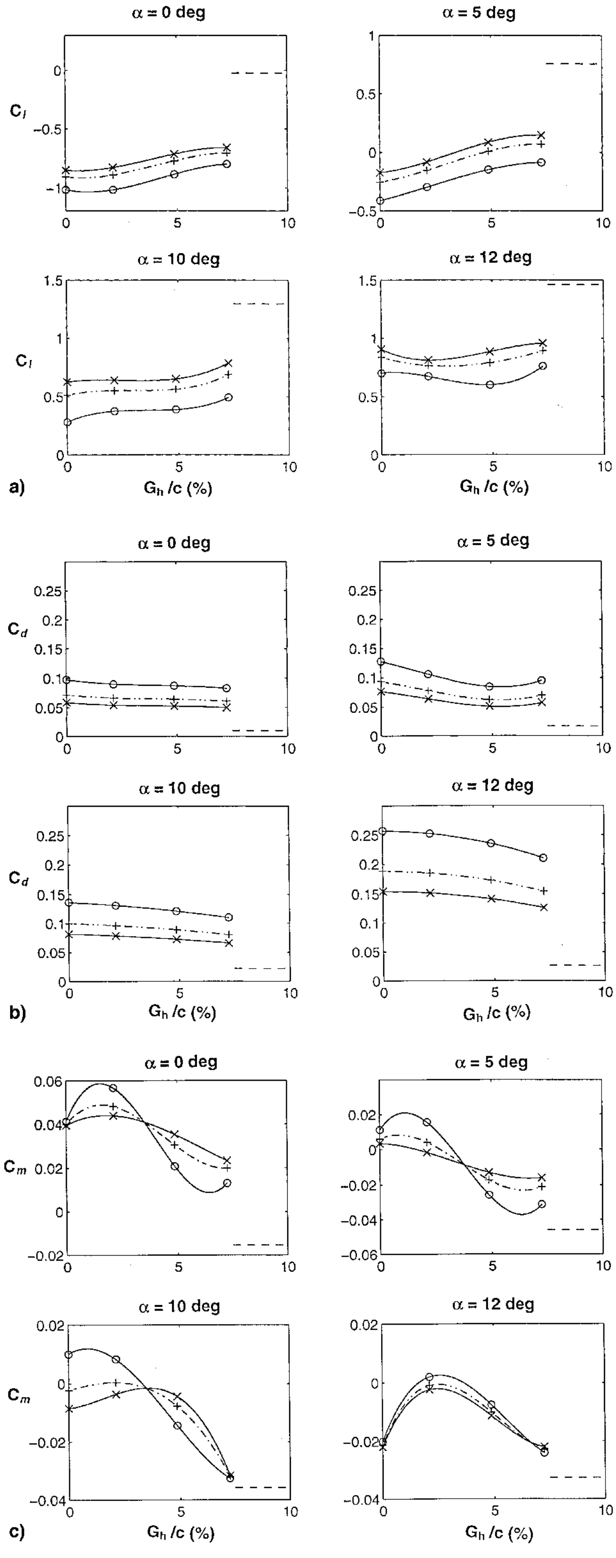

Fig. 3 Effects of gap size and inclination on static a) lift, b) drag, and c) pitching moment. ---, without spoiler; ○, θ = 90 deg; +, θ = 75 deg; and ×, θ = 60 deg.

the static characteristics of the present model were close to the standard data,[7] even though the present Reynolds number was at least one order of magnitude lower. Lift, drag, and pitching moment were measured simultaneously, but the focus was on the variations of lift C_l and moment C_m. Base-venting is quantified here by G_h, which is defined as the shortest distance between the airfoil upper surface and the lower tip of the base-vented spoiler deflected at $\theta = 90$ deg. Dynamic tests were carried out at four values of $G_h/c = 0$, 2, 4.9, and 7.2%, three spoiler deflections, $\theta = 60$, 75, and 90 deg; four angles of attack, $\alpha = 0$, 5, 10, and 12 deg, and a wide range of spoiler angular speed, $100 < \omega < 1200$ deg/s.

To appreciate how base-venting affects the static values of lift and moment, variations of static C_l, C_d, and C_m with respect to gap size at $\theta = 60$, 75, and 90 deg and $\alpha = 0$, 5, 10, and 12 deg are plotted in Fig. 3 together with the static values of an airfoil without the spoiler, as represented by the dashed lines. As depicted, lift was substantially reduced and moment was increased by the presence of the spoiler at the gap sizes tested. And as the gap size was increased, both lift and moment asymptotically approached the values of a clean airfoil, which could be viewed as an airfoil having a spoiler with $G_h/c \rightarrow \infty$. Interestingly, the trends at $\alpha = 0$, 5, and 10 deg are quite similar, especially the difference, $C_l(\theta = 60\text{ deg}) - C_l(\theta = 90\text{ deg})$, being independent of G_h/c. Early flow separation taking place upstream of the spoiler when the airfoil is at large angles of attack may affect the variations of C_l and C_m at $\alpha = 12$ deg, such that the trends are unique. As shown in Fig. 4, lift, drag, and moment on the airfoil because of the presence of the stationary spoiler at $\theta = 60$, 75, and 90 deg and $G_h/c = 0$, 2, 4.9, and 7.2% are compared with those of the clean airfoil at various α. It is rather surprising to find that the lift-curve slope, $\partial C_l/\partial\alpha$, which is related to the mean camber of the airfoil-spoiler system, remains approximately the same in the range of gap size tested. In other words, Fig. 4 suggests that the static characteristics of the airfoil with a conventional spoiler are not affected by base-venting, if $0 \leq G_h/c \leq 7.2\%$.

The adverse effects of C_l, C_m, and C_d induced by a conventional spoiler (i.e., $G_h/c = 0$) are obviously shown in Fig. 5 with respect to nondimensional time Ut/c during the spoiler rotation from $\theta = 0$ to 90 deg at $\alpha = 0$ deg. The opening time of the spoiler is $T = 0.145$ s or $UT/c = 4.4$, and corresponds to $\omega = 620$ deg/s or $\omega c/U = 0.36$. The C_{la}, C_{ma}, and the aerodynamic delays t_a/T are found to decrease with increasing UT/c, as shown in Fig. 6. Although tested at different conditions, the present results of t_a/T are in good agreement with the data from Ref. 1. The lower values of C_{la} from Ref. 1 are perhaps because the spoiler used there only partially spans the airfoil.

When base-venting is introduced, the adverse values of C_l and C_m diminish with increasing gap size, as depicted in Fig. 7 at $\alpha = 0$ deg and $\omega c/U = 0.36$, with θ changed from 0 to 90 deg, indicating that the proposed method is effective in the

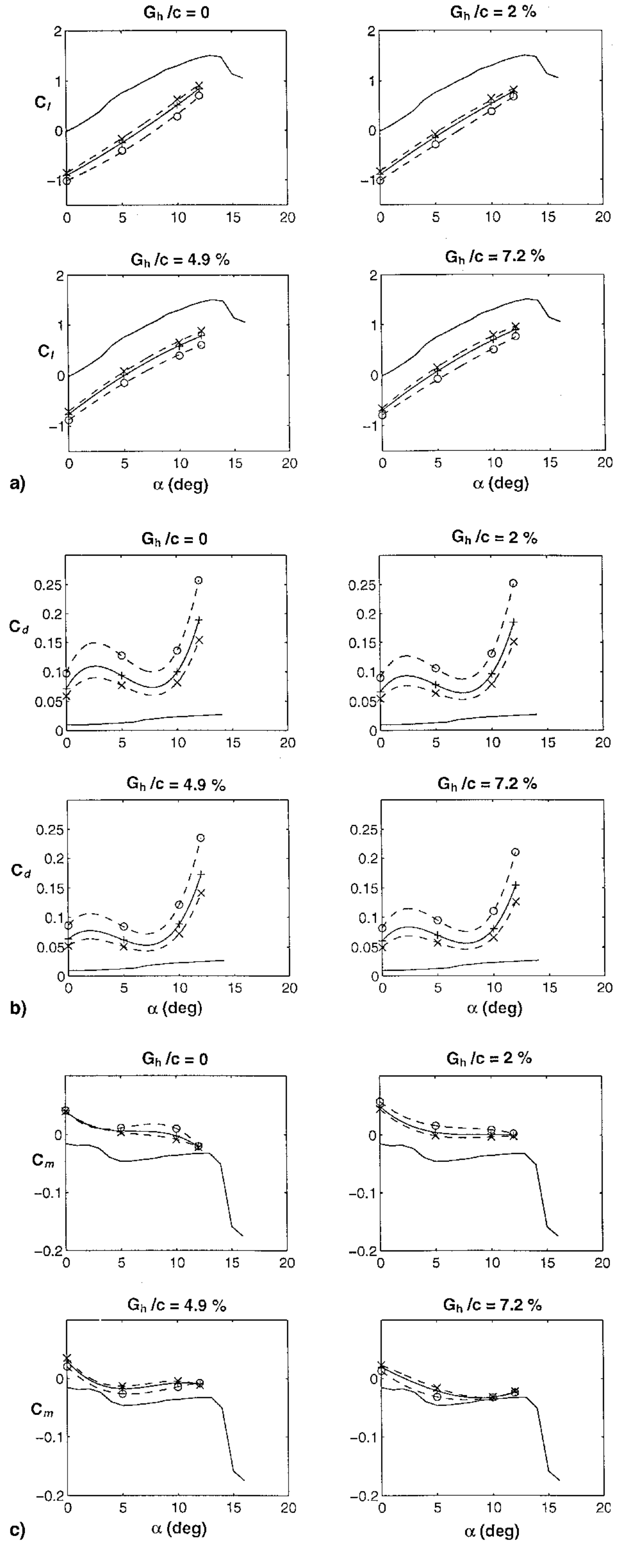

Fig. 4 Static characteristics of NACA 0012 with spoiler a) lift, b) drag, and c) pitching moment. ——, without spoiler; ○, θ = 90 deg; +, θ = 75 deg; and ×, θ = 60 deg.

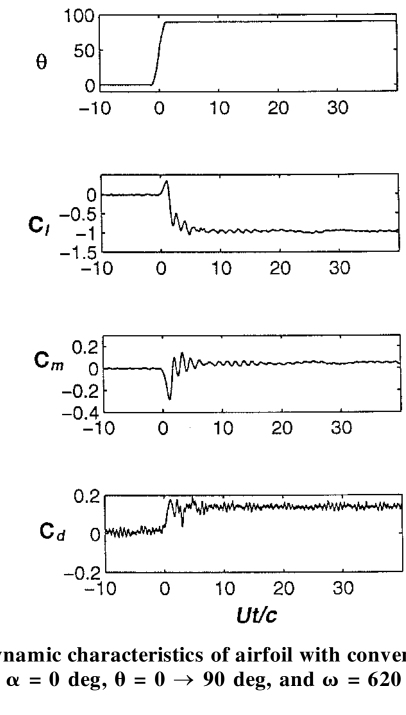

Fig. 5 Dynamic characteristics of airfoil with conventional spoiler ($G_h/c = 0$). $\alpha = 0$ deg, $\theta = 0 \rightarrow 90$ deg, and $\omega = 620$ deg/s.

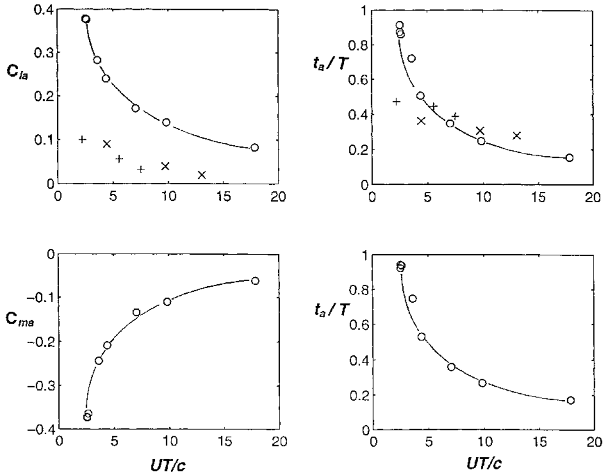

Fig. 6 Variations of adverse lift, moment, and aerodynamic delay (α = 0 deg). Present ○, θ = 0 → 90 deg and ω = 620 deg/s; Ref. 1 +, θ = 0 → 35 deg and ω = 5500 deg/s; and Ref. 1 ×, θ = 0 → 35 deg and ω = 2800 deg/s.

reduction of adverse effects. Figures 8 and 9 summarize the variations of C_{la} and C_{ma} with respect to G_h/c at fixed values of α, ω, and θ. The reduction is seen to be most effective from G_h/c = 0 to 2% for the range of ω tested. The nonlinear variations of C_{la} and C_{ma} with UT/c at G_h/c = 0 in Fig. 6 suggest that they may vary linearly with $\omega c/U$. And indeed, the linear variations have been confirmed in Figs. 10 and 11 at α = 0 and 5 deg and θ = 60, 75, and 90 deg. However, what is more unexpected is that after base-venting is introduced, these variations remain linear with gradients, $\partial C_{la}/\partial(\omega c/U)$ and $\partial(-C_{ma})/\partial(\omega c/U)$, decreasing as the gap size is increased.

The spoiler deflection is usually greater than 45 deg to be effective in increasing the drag to slow down the airplane during landing. As a result, only three deflections, i.e., θ = 60, 75, and 90 deg, were tested. Studying Figs. 10 and 11 again reveals that the magnitudes of C_{la} and C_{ma} at θ = 60 deg are larger than those at θ = 75 and 90 deg at fixed gap sizes and angles of attack. For instance, at G_h/c = 0, α = 0, and $\omega c/U \cong 0.29$, Fig. 10 shows that $C_{la}(\theta = 60\text{ deg}) \cong 0.3$, $C_{ma}(\theta = 60\text{ deg}) \cong -0.23$; whereas $C_{la}(\theta = 90\text{ deg}) \cong 0.2$ and $C_{ma}(\theta = 90\text{ deg}) \cong -0.18$. If $\omega c/U$ is fixed, a smaller value of θ means a smaller T. Therefore, according to the trends in Fig. 6, it is

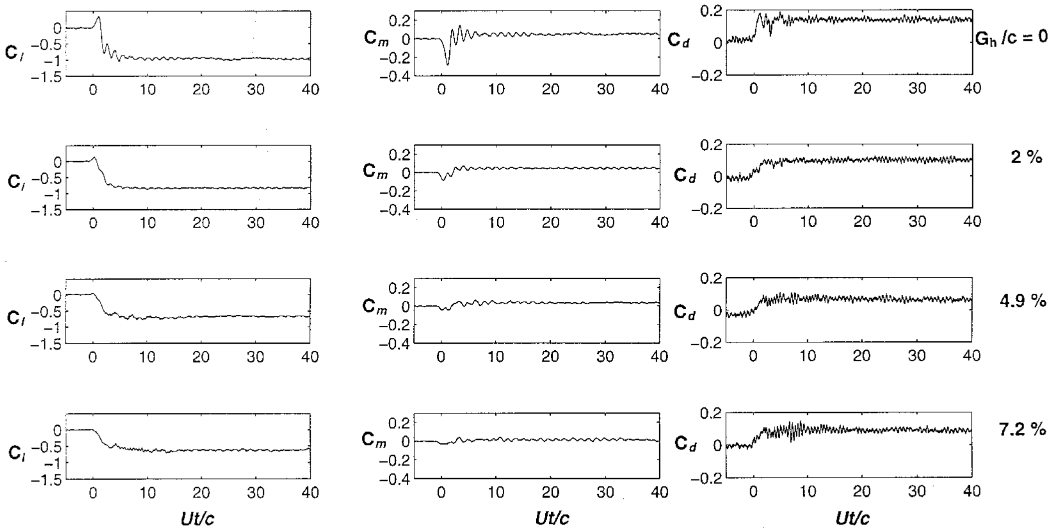

Fig. 7 Transient lift, moment, and drag of base-vented spoiler. α = 0 deg, θ = 0 → 90 deg, and ω = 620 deg/s.

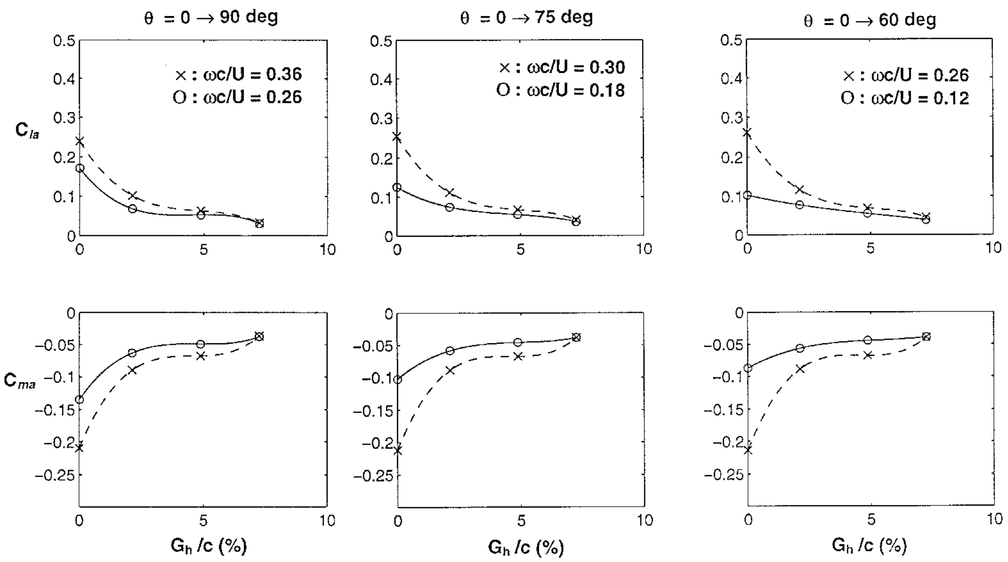

Fig. 8 Variations of adverse lift and moment with gap size (α = 0 deg).

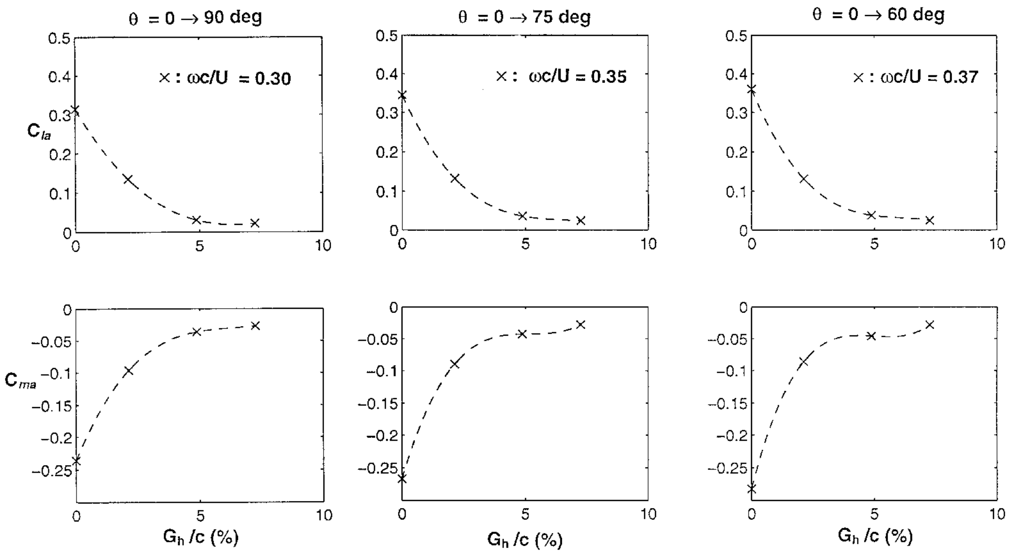

Fig. 9 Variations of adverse lift and moment with gap size (α = 5 deg).

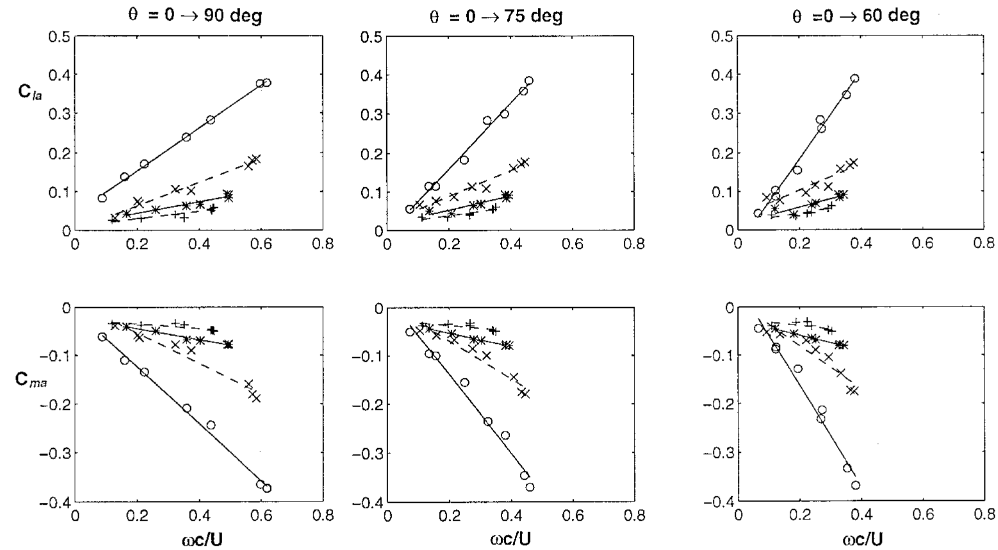

Fig. 10 Variations of adverse lift and moment with angular speed (α = 0 deg). ○, G_h/c = 0; ×, G_h/c = 2%; *, G_h/c = 4.9%; +, G_h/c = 7.2%.

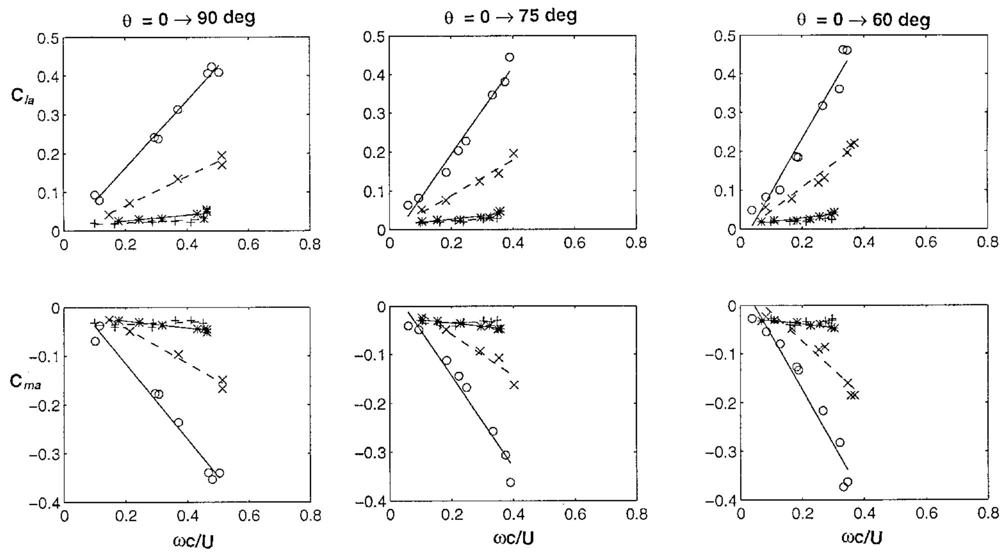

Fig. 11 Variations of adverse lift and moment with angular speed (α = 5 deg). ○, G_h/c = 0; ×, G_h/c = 2%; *, G_h/c = 4.9%; +, G_h/c = 7.2%.

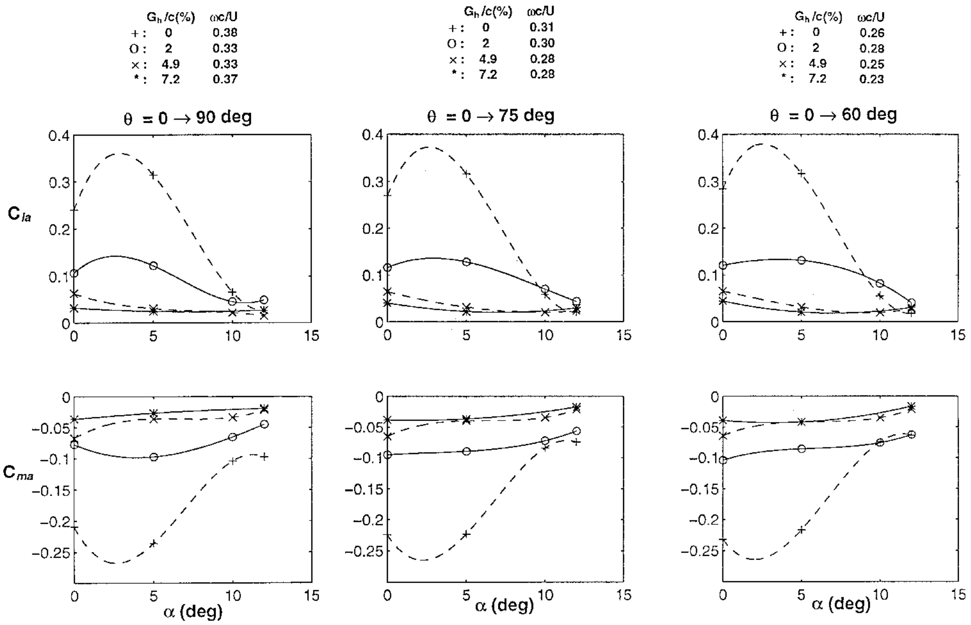

Fig. 12 Variations of adverse lift and moment with angle of attack.

still reasonable to predict that the magnitudes of C_{la} and C_{ma} increase with decreasing θ. Certainly, θ has to be larger than zero to generate the starting vortex.

The static effectiveness of spoilers, in general, is seriously affected by early flow separation near the leading edge of the airfoil, as often encountered at large angles of attack. The same trend applies to the adverse effects (Fig. 12). For example, at $\theta = 90$ deg, $\omega c/U = 0.38$, $G_h/c = 0$, the magnitudes of C_{la} and C_{ma} increase initially between $\alpha = 0$ and 5 deg, but decrease when $\alpha > 5$ deg. The same patterns are observed when θ is reduced to 75 or 60 deg. For the base-vented spoiler, the corresponding variations are much smaller because most of the adverse effects have been reduced.

Concluding Remarks

The experimental data suggest that the adverse effects caused by a rapidly moving spoiler may be reduced by introducing base-venting between the spoiler and the airfoil. The flow through the gap reduces the effect of the strong starting vortex shed from the upper tip of the spoiler. In particular, the magnitudes of adverse lift and moment 1) decrease with increasing gap size, 2) increase linearly with the angular speed of spoiler, 3) decrease with increasing spoiler deflection, and 4) increase initially but decrease eventually with the angle of attack of the airfoil. The static lift and moment of an airfoil with a conventional spoiler, however, may not be affected by base-venting if the gap size is within the range as investigated in the present study.

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