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Suppression of Dynamic-Stall Vortices over Pitching Airfoils by Leading-Edge Suction

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Experiments to control the dynamic-stall vortex (DSV) over the suction surface of a two-dimensional NACA 0012 airfoil, undergoing a hold-pitch-hold motion, are described. Measurements were performed over a range of Reynolds number ($3.0 \times 10^4 \le Re_c \le 1.18 \times 10^5$) and pitch rate ($0.072 \le \alpha^+ \le 0.31$), using leading-edge suction during a prescribed period of the airfoil motion. This strategy to manage the DSV, using controlled leading-edge suction, was developed from a study of the mechanisms responsible for the evolution of the vortex. The results indicate that formation of the DSV can be suppressed by removing an appropriate amount of the reverse-flowing fluid to prevent its accumulation in the near-leading-edge region, thereby preventing lift up of the shear layer. The influence of different parameters such as pitch rate, Reynolds number, suction timing, and suction-slot size and location on the control of the DSV is described. A scaling is developed for the suction flow rate that provides valuable information about the growth of the reverse-flow region and its dependency on different parameters. Parameter ranges are identified for which complete or partial suppression of the DSV can be achieved.

Nomenclature

c	= airfoil chord
Q_{nd}	= dimensionless suction flow rate, $\dot{Q}_s/(U_\infty c^2)$
Q_{rf}	= reverse-flow accumulation rate
Q_s	= suction flow rate
Re_c	= Reynolds number based on chord, $U_\infty c/\nu$
t_p	= airfoil pitch time for angle $\Delta\alpha$
Up	= tangential velocity of the airfoil nose
U_{rf}	= average reverse-flow velocity
U_∞	= freestream velocity
W_s	= slot width
α	= airfoil angle of attack
α^+	= dimensionless pitch rate, $(\Delta\alpha c)/(t_p U_\infty)$
$\dot{\alpha}$	= angular velocity, rad/s
$\Delta\alpha$	= change in angle of attack
ν	= kinematic viscosity

Background and Objectives

THE study of unsteady flow over pitching airfoils has been largely motivated by the need to understand helicopter-blade aerodynamics, and more recently, by interest in aircraft supermaneuverability. In the case of rapidly pitching airfoils, delay of flow separation on the upper surface results in an additional, transient component to the lift force obtained under static conditions. This increased aerodynamic lift is caused by the formation of a coherent vortical structure, referred to as the dynamic-stall vortex (DSV). A system that is to successfully manage and control this unsteady, separated flow, and thus the aerodynamic behavior of rapidly pitching airfoils, must first be able to monitor and control the DSV.

Depending on the application, the objectives of unsteady, separated flow management may be very different. For example, in helicopter applications the formation of the DSV is undesirable altogether, and the objective of flow control could be to prevent its occurrence in the leading-edge region of rotor blades. In the case of highly maneuverable aircraft, the objective could be to take advantage of the increased dynamic lift by allowing the DSV to form but to delay detachment and shedding of the DSV from the airfoil suction surface, thereby delaying dynamic stall.

A great deal of effort has been devoted to investigations of this complex flowfield, to develop an understanding of the physical mechanisms that lead to the formation of the dynamic-stall vortex. Excellent reviews by McCroskey,[1] Gad-el-Hak,[2] and Ericsson and Reding[3] summarize most of this work. Recent studies at Illinois Institute of Technology[4,5] (IIT) have revealed important information about the evolution of unsteady pressure field and vorticity production over the surface of a two-dimensional airfoil model. Computational work by Visbal,[6] with an emphasis on the initial stage of the formation of the DSV, has also provided useful insight to the problem. As a follow up to the work by Metwally, Karim[7] examined the initial stages of the formation of the DSV. His results, and additional experiments reported by Acharya et al.,[8] provide a further understanding of the mechanisms responsible for the formation of the DSV and the basis for the development of a strategy for its control.

This paper reports on the use of leading-edge suction as one possible strategy for flow control for two-dimensional pitching airfoils. It examines the effectiveness of this approach to suppress the formation of the DSV. The influence of different parameters such as pitch rate, Reynolds number, suction timing, and suction-slot size and location on the control of the DSV is also described. The overall goal of work of this nature is to develop control techniques which can be used ultimately for flow management in highly maneuverable aircraft. Such applications involve flow over three-dimensional shapes, high Reynolds number, and lower dimensionless pitch rates. The applicability of leading-edge suction or other control strategies for flow management under these conditions remains to be established. Although we report only on the effectiveness of leading-edge suction to suppress the DSV, other control objectives, such as alteration, delay in detachment, or enhancement of the DSV, are also appropriate, and further experiments are needed to examine the effectiveness of leading-edge suction in meeting these objectives.

Experimental Arrangement

Wind Tunnel

The experiments were conducted in the Andrew Fejer Unsteady Wind Tunnel at IIT's Fluid Dynamics Research Center. This is a closed-circuit, low-speed facility, driven by an axial-vane fan powered by a 40-hp synchronous motor. The wind-tunnel test section is 0.61 m × 0.61 m in cross section and 3.1 m in length. Flow velocities up to 40 m/s can be reached by adjusting a magnetic clutch excitation, which controls the fan rotational speed. Screens,

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honeycombs, and a contraction region upstream of the test section yield a turbulence level of 0.03% at the maximum velocity. Controlled oscillation of a shutter mechanism, mounted at the downstream end of the test section, can produce an unsteady flow component. A controlled, unsteady motion can also be imparted to a model positioned in the flow.

Airfoil Model

The airfoil model used for this investigation had an NACA 0012 profile, with a chord length of 30 cm, a thickness of 12% chord, and a span of 60 cm. The model was made hollow to accommodate tubing for surface-pressure measurements and to make room for suction and blowing chambers. Details of its design and construction are described by Metwally.[4]

A special feature of the airfoil design provided the ability to withdraw fluid from a spanwise suction slot placed in the near-leading-edge region of the suction surface. A suction chamber with a volume of 50 cm^3 was built into the leading-edge region and connected to the slot. The slot width could be changed by changing the width of an insert. The slot could be located at 2% or 5% of chord from the leading edge. In the present investigation, slot widths of 0.5 mm and 2 mm were used at the two locations. Another feature of the airfoil, not used in the present experiments, provided the ability to introduce a two-dimensional jet into the airfoil wake, through a blowing manifold connected to a spanwise, trailing-edge slot.

The airfoil was mounted in the horizontal midplane of the test section, allowing it to pitch about its quarter-chord pivot line. The model was driven by a low-inertia, high-torque, servocontrolled dc motor with an analog servoamplifier. A Schaevitz R30D rotary-variable-differential transformer (RVDT) was used to obtained a signal proportional to the airfoil angular position.

Suction System

The airfoil suction chamber was divided into five compartments to achieve uniform suction across the span. These compartments were connected by flexible tubes to a circular distributor located inside the airfoil. The distributor was connected to an evacuated tank located outside the tunnel, through a high-vacuum, direct-acting solenoid valve. The trapped-vortex pair (TVP) flow meter described in the next section was mounted between the distributor and the solenoid valve. The solenoid valve was actuated by signals from the minicomputer to enable suction through the leading-edge slot at predetermined angles while the airfoil was in motion. The vacuum tank was evacuated to a specified vacuum level prior to each experimental run, to obtain the desired suction flow rate.

Instrumentation

Smoke-wire flow visualization was used to examine the flowfield over the pitching airfoil. A 0.1-mm-diam nichrome wire was coated with oil droplets and heated electrically, causing the droplets to vaporize, thereby producing uniform streaklines of smoke. The streak lines passing over the model were illuminated and photographed at the appropriate instant.

A vertical smoke wire, placed one chord length upstream of the nose in the central plane of the airfoil, was used to examine the overall flowfield. This produced a sheet of streaklines in the central plane, perpendicular to the airfoil span. To examine the near-wall flow structures, another smoke wire was positioned spanwise across the airfoil, at an adjustable height, 0.2–1 mm from the airfoil surface. This produced a spanwise sheet of smoke in the near-wall region over the suction surface. A four-bar mechanism mounted on the airfoil model was used to hold the smoke wire to the airfoil, allowing it to remain stationary with respect to the pitching airfoil.

A TVP flow meter developed by Mansy and Williams[9] was used to measure the volumetric flow rate of the fluid withdrawn by suction from the near-leading-edge region. The design of this device results in a jet of fluid that issues into a cavity. A pair of counter-rotating vortices produced in the cavity oscillate as the result of an instability. The oscillation frequency is directly proportional to the volumetric flow rate of the jet. The pressure difference measured between the two sides of the flow-meter axis exhibits the same periodicity as the vortex oscillation. The frequency of this differential-pressure signal is related, through calibration, to the flow rate to be measured. A model DP103 Validyne pressure transducer in combination with a model CD15 Validyne carrier demodulator was used to measure the TVP pressure signal.

A Masscomp minicomputer was used for all of the data acquisition and processing.

Parameter ranges

A hold-pitch-hold ramp-up motion of the model at constant velocity was used, covering a range of α^+ between 0.072 and 0.31. The feasibility of leading-edge suction for controlling the dynamic-stall vortex was examined for airfoil pitchup from 0 to 60 deg over a range of chord Reynolds numbers from 30,000 to 118,000. Slot locations, slot widths, and ranges of other parameters associated with the suction are identified in later sections.

Strategy for Control of the Dynamic-Stall Vortex

The control strategy was developed from a study of the initial stages in the formation of the DSV that identified the principal mechanisms playing a role in this process. Acharya et al.[8] provide a detailed description of this process and the evolution of the DSV. A few important results are described to develop the basis for the control strategy.

As the airfoil begins its pitching motion, the stagnation point that is initially at the nose of the airfoil moves down the pressure surface, and a strong suction peak develops near the leading edge on the airfoil suction surface. The region between the stagnation point and this leading-edge suction peak experiences a strong, favorable pressure gradient. A concentrated vorticity source located in this region introduces negative, or clockwise, vorticity into the flow. For most of the airfoil motion, this source remains between the airfoil nose and 2% of chord on the pressure side. The fluid containing this clockwise vorticity is confined to a thin shear layer that remains close to the surface initially and is transported by the shear layer around the nose and over the suction surface. The shear

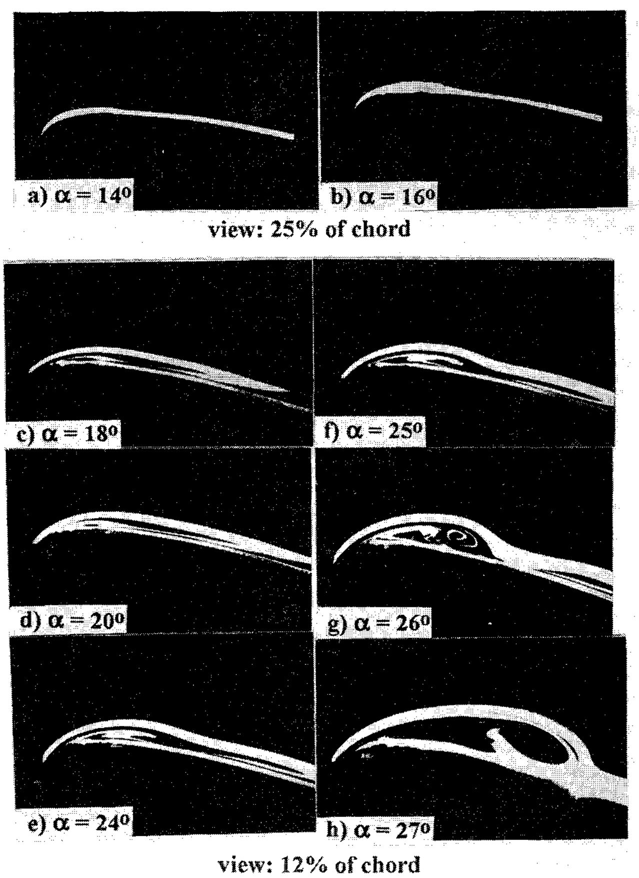

Fig. 1 Flow-visualization records showing development of the DSV over a pitching airfoil; $\alpha^+ = 0.31$ and $Re_c = 30{,}000$.

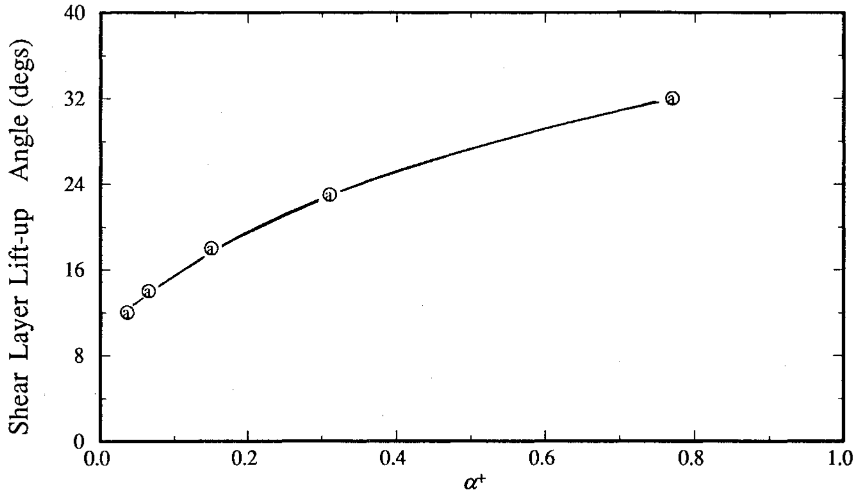

Fig. 2 Variation of shear layer liftup angle with pitch rate.

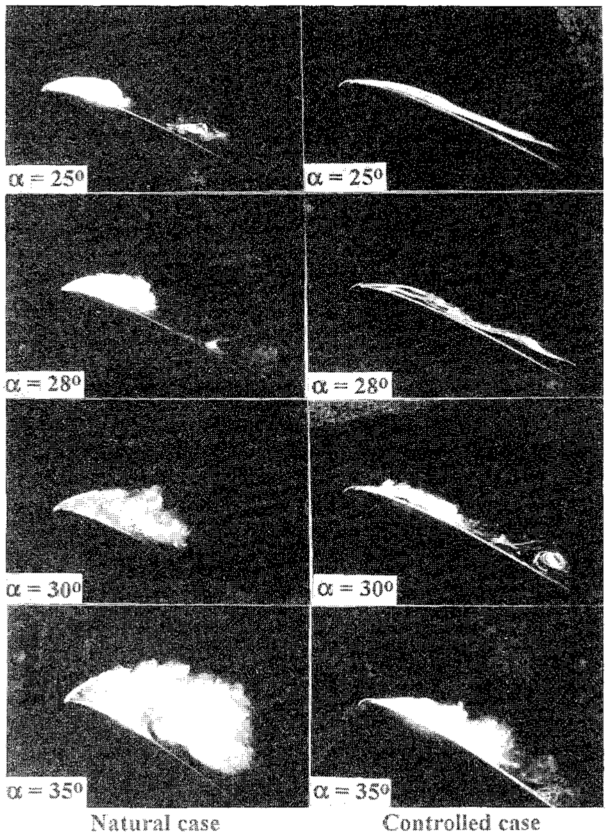

Fig. 3 Effect of suction on flow development during pitchup of airfoil; $\alpha^+ = 0.15$, $Re_c = 30{,}000$, and $Q_{\rm nd} = 0.0127$, view shown 67% of airfoil suction surface.

layer has to negotiate an adverse pressure gradient that exists downchord of the suction peak location. As the airfoil continues to pitch up, this adverse pressure gradient increases, slowing down the shear layer, and resulting in an accumulation of vorticity near the leading edge. This is seen by a thickening of the streaklines in Figs. 1a and 1b. The effect of the adverse pressure gradient becomes more severe with increase in the airfoil angle, and eventually builds up to a point where low-momentum fluid close to the surface slows down sufficiently to produce a region of local reverse flow (Fig. 1c) over the forward portion of the suction surface, between 5% and 10% of the chord. This local, unsteady, reverse flow plays a crucial role in the formation of the dynamic-stall vortex. The reverse-flow layer, which transports fluid particles upchord along the airfoil suction surface, initially remains thin and close to the surface. As the pitchup continues, the fluid transported by the reverse flow begins to accumulate in the vicinity of the leading edge and forces the shear layer to lift away from the airfoil suction surface (Fig. 1d). With increasing accumulation of fluid, the shear layer is pushed farther away from the surface and develops a kink toward the outer flow (Fig. 1e). As the airfoil angle increases, the region of accumulated reverse-flowing fluid also expands in the chordwise direction (Fig. 1f). Downstream of this zone of accumulating, reverse-flow fluid, the pressure continues to increase. This results in a further slowing down of the fluid in the shear layer as additional fluid containing clockwise vorticity continues to arrive. At the same time, the shear layer liftup process continues upchord, as more reverse-flowing fluid accumulates underneath the shear layer. At 26-deg angle of attack (Fig. 1g), a recirculating zone of reverse-flow fluid is observed. The accumulation of clockwise vorticity downstream of this zone, caused by the adverse pressure gradient, combines with the outer flow to initiate an instability or a rollup of the shear layer as seen at 27-deg angle of attack (Fig. 1h). This is the first appearance of the dynamic-stall vortex, formed by the rollup of distributed vorticity in the shear layer into a large-scale vortical structure. The DSV remains compact and stationed over the airfoil surface for a further period, during which it continues to accumulate vorticity from the shear layer. A very abrupt secondary flow feature—a strong, transverse eruption of near-wall fluid, very narrow in streamwise extent and just upstream of the DSV—results in the separation of the DSV from the shear layer. After this stage, the DSV detaches from the surface, grows very rapidly, and convects downstream.

The accumulation of reverse-flowing fluid in the leading-edge region is responsible for the shear layer liftup. Subsequent accumulation of vorticity and rollup of the shear layer causes the formation of the dynamic-stall vortex. This suggests that prevention or delay of the shear layer liftup might help control the dynamic-stall vortex formation. To eliminate shear layer liftup, we need to prevent accumulation of the reverse-flowing fluid in the leading-edge region. This observation suggested the control strategy for suppression of the DSV that we examine in this study: remove the reverse-flowing fluid at the same rate as it arrives in the leading-edge region, through a spanwise slot placed appropriately in the suction surface. Other objectives, such as delaying the detachment of a formed DSV, can be met by changing the rate at which this fluid is removed.

Information on the angle at which liftup occurs is important for the control experiments. The variation of this angle with the dimensionless pitch rate, plotted in Fig. 2, shows that events in the evolution of the DSV are delayed to higher angles as the pitch rate increases.

Results of Control Experiments

Evaluation of Control Strategy

The suction concept just described was tested in experiments, in which fluid was withdrawn through a suction slot at a wide range of rates. Figure 3 compares the result of such an experiment at one suction flow rate, to the flowfield without suction control. These photographs show a view of 67% of the suction surface and were taken at four different angles of attack, while the airfoil was pitching from 0 to 45 deg with $\alpha^+ = 0.15$. The spanwise smoke wire was positioned at the nose, 1 mm from the surface. The dimensionless suction flow rate Q_{nd} for the controlled case was 0.0127, and suction was initiated at 6-deg angle of attack during pitchup of the airfoil, through a spanwise slot at 2% chord. As discussed in a later section, this flow rate was found to be the optimum suction rate for this flow condition and 35-deg angle of attack. The pictures with suction control show that the shear layer remains close to the surface; the negative vorticity produced in the leading-edge region convects downstream along the suction surface of the airfoil. At the high angles of attack, the smoke streak becomes thicker and transition to a turbulent state is observed. On the other hand, in the natural cases with no suction control, a fully grown dynamic-stall vortex is seen over the suction surface of the airfoil. Based on the experimental results that follow, it is argued that optimum suction removes the necessary amount of near-wall fluid through the suction slot to prevent accumulation of reverse-flowing fluid. Shear layer liftup no longer occurs near the leading edge, thereby preventing formation of the DSV. It is this mechanism, rather than removal of fluid from the shear layer that flows downchord, that suppresses the dynamic-stall vortex. The shear layer fluid is not removed; its agglomeration and rollup into a vortex is prevented.

The results presented in following sections show that formation of the DSV, the shedding of which culminates in dynamic stall, can be suppressed for a range of flow parameters by removing a small amount of fluid from the near-wall region. On the basis of the experimental evidence, it is reasoned that this suction removes fluid that would otherwise accumulate in the leading-edge region, resulting in liftup of the shear layer. The level of control required for either complete or partial suppression of the DSV is established by changing the rate at which fluid is removed from the leading-edge region.

The control strategy is based on the amount of fluid removed from the near-wall region rather than the suction pressure level or velocity at the suction slot. Other parameters, such as suction activation time, deactivation time, and slot location also affect the control process. The influence of these parameters, as well as controllability, and limitations with increase in chord Reynolds number and angle of attack are addressed in the following sections. Some scaling properties are also discussed.

Scaling of the Suction Flow Rate

Complete suppression of the DSV requires that reverse-flowing fluid be removed from the leading-edge region at a specific rate. An examination of the scaling that governs this suction flow rate provides a way to validate the concept as well as insight to the growth of the reverse-flow region and its dependency on different parameters. Dimensional analysis, with the variables freestream velocity U_∞, a characteristic length, taken to be the chord length c, the angular velocity of the airfoil $\dot{\alpha}$, suction flow rate $\dot{Q}_s$, fluid density ρ and viscosity μ results in three dimensionless groups: $\dot{Q}_s/U_\infty c^2$, $\dot{\alpha}c/U_\infty$, and $U_\infty c/\nu$. The last two are the dimensionless

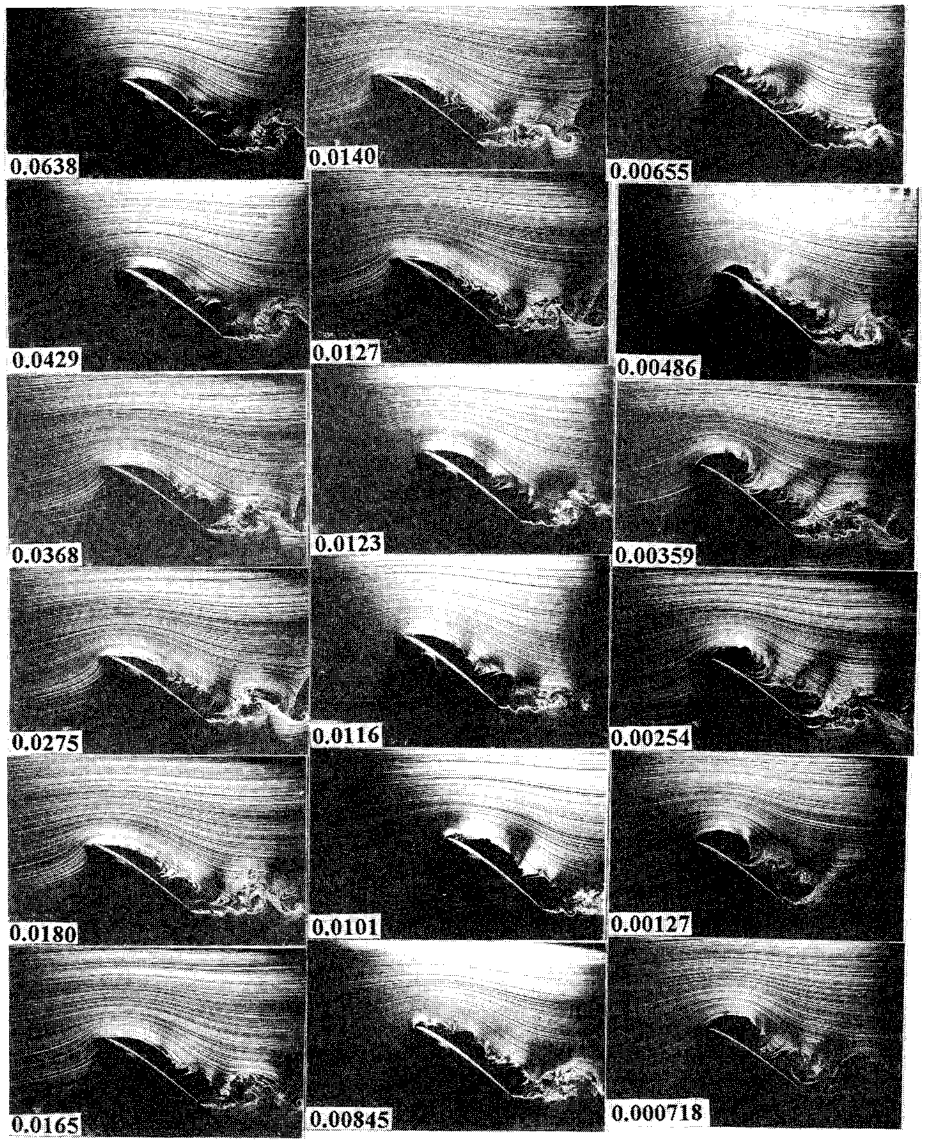

Fig. 4 Influence of suction flow rate on the development of the DSV; $\alpha^+ = 0.15$, $Re_c = 30{,}000$, and $\alpha = 35$ deg.

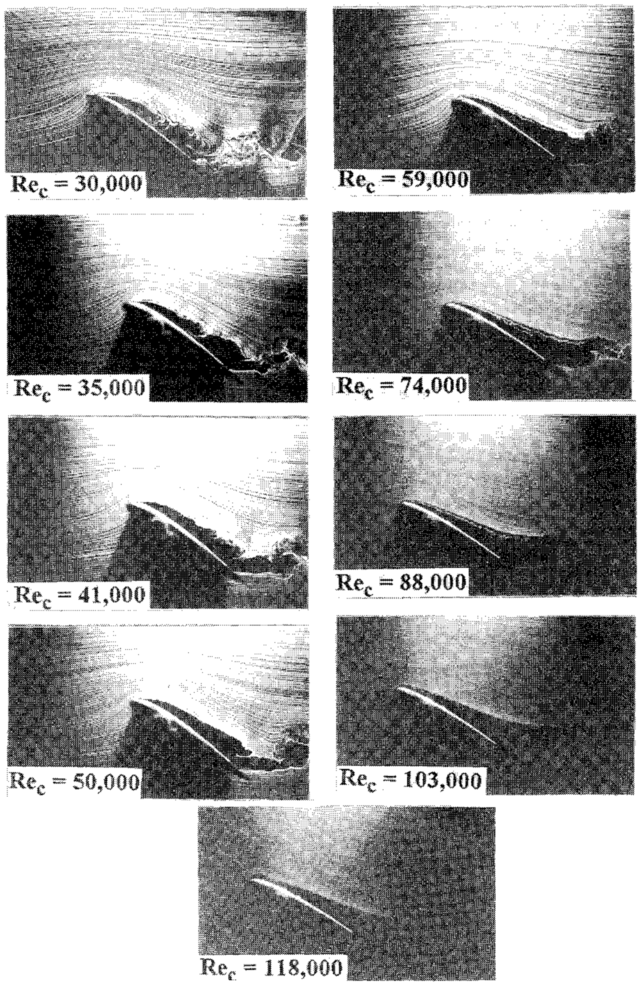

Fig. 5 State of flowfield over a pitching airfoil; $\alpha^+ = 0.15$ and $\alpha = 35$ deg for different Re_c, with a dimensionless suction flow rate of 0.0127.

pitch rate α^+ and chord Reynolds number Re_c, respectively. The control strategy calls for a balance between the rate of suction $\dot{Q}_s$ and the reverse-flow accumulation rate $\dot{Q}_{\mathrm{rf}}$. A simplified model of the near-wall process is used to obtain an expression for the latter and relate the two rates. The dimensionless pitch rate $\dot{\alpha}c/U_\infty$ is the ratio between a convective time scale c/U_∞ and the time scale of the airfoil motion $1/\dot{\alpha}$. For a fixed chord length c and angular velocity $\dot{\alpha}$, the convection time scale decreases relative to the airfoil motion time scale as U_∞ increases, resulting in an increase in the accumulation rate. Thus, the accumulation rate is inversely proportional to the convective time scale. The rate of growth of the reverse-flow (viscous) region, on the other hand, is proportional to the viscous length scale ν/U_p and convective time scale (c/U_∞). The ratio of these two scales provides a measure of the accumulation rate U_{rf} of reverse-flowing fluid. Thus the volumetric rate $\dot{Q}_{\mathrm{rf}}$ is proportional to $U_\infty(\nu/\dot{\alpha})$, i.e., $U_p \sim c\dot{\alpha}$ and $\dot{Q}_{\mathrm{rf}} \sim U_{\mathrm{rf}}c^2$. Comparison of the two rates $\dot{Q}_{\mathrm{rf}}$ and $\dot{Q}_s$ yields the appropriate scaling. The control strategy requires that the ratio $\dot{Q}_s/\dot{Q}_{\mathrm{rf}}$ remains constant for a given dimensionless pitch rate (i.e., a fixed ratio between the convective time scale and the time scale of airfoil motion) and angle of attack. Therefore, the required suction flow rate for a particular value of α^+ and angle of attack is given by

$$(\dot{Q}_s/U_\infty)\,(\dot{\alpha}/\nu) = \text{const}$$

or

$$\dot{Q}_s/(U_\infty c^2)\,(\dot{\alpha}c/U_\infty)\,(U_\infty c/\nu) = \text{const}$$

or

$$(\dot{Q}_s/U_\infty c^2)\,\alpha^+ Re_c = \text{const}$$

which is the product of the three dimensionless groups obtained by dimensional analysis. The constant needs to be determined by experiment for different pitch rates, Reynolds number, and angle of attack.

Experimental Determination of the Optimal Flow Rate

The effect of varying the suction flow rate over two orders of magnitude was examined for the conditions of Fig. 3. Suction was activated at an angle of 6 deg, and the set of flow-visualization records shown in Fig. 4 was obtained at an angle of 35 deg during the pitchup. For values of the dimensionless suction flow rate from 0.064 to 0.0123, there is no significant difference in the flowfield over the airfoil suction surface. Below a rate of 0.0123, ability to suppress the DSV is progressively degraded. For a suction of 0.0101, the development of a vortex is seen near the leading-edge region. At 0.000718, the last record in the figure, the flow over the suction surface resembles the natural case (without suction control).

If the earlier description of the physical processes is accurate, removing fluid by suction at a rate higher than that needed to prevent accumulation of reverse-flowing fluid should not produce any additional improvement in the flow state. This should result only in removal of some additional fluid with negative vorticity from the shear layer. Results for suction rates larger than 0.0127 support this argument. Suction at a rate lower than the accumulation rate of the reverse-flowing fluid should result in some accumulation in the leading-edge region and, therefore, only a partial suppression of the DSV. In addition, partial removal of the reverse-flowing fluid should slow down the rate of accumulation and lead to a delay in the vortex formation with a smaller vortex compared to the natural state at the same angle of attack. Results for suction rates smaller than 0.0127 validate this reasoning. Although the accumulation rate is not measured directly, it is logical to argue that for the experimental conditions already described, a suction rate of 0.0127 removes reverse-flowing fluid at the accumulation rate and that for each set of flow conditions, there must be an optimum suction flow rate which prevents any accumulation of reverse-flowing fluid, thereby suppressing the vortex completely. The optimum conditions must be defined for a specific control objective, such as complete suppression of the vortex. Different objectives, such as partial control or delaying the detachment of a formed DSV, would result in different optimum specifications.

Effect of Freestream Velocity and Pitch Rate at Different Angles of Attack

Experiments were carried out to examine the influence of freestream velocity and pitch rate on the control of the dynamic-stall vortex at different angles of attack. A 0.5-mm-wide slot, located at 2% chord, was used. The objective of control was com-

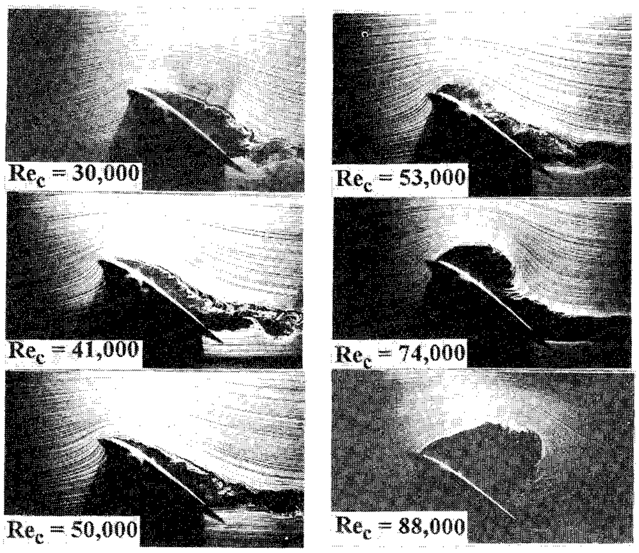

Fig. 6 State of flowfield over a pitching airfoil; $\alpha^+ = 0.072$ and $\alpha = 35$ deg for different Re_c, with a dimensionless suction flow rate of 0.109.

plete suppression of the dynamic-stall vortex. The minimum suction flow rate required to achieve this control was chosen to be the optimum rate. For all of the experiments described, suction was activated at 6-deg angle of attack during pitchup of the airfoil.

Figure 5 shows that suction with $Q_{nd} = 0.0127$ provides control at 35 deg, for $\alpha^+ = 0.15$ over a Reynolds number range of 30,000–118,000. Note that for a fixed value of α^+, the product $(\dot{Q}_s/U_\infty c^2) Re_c$ is independent of U_∞. The data of Fig. 5 substantiate this. Data at $\alpha^+ = 0.10$ for the same conditions also confirm the scaling argument and model for reverse-flow accumulation, with a higher value (0.0429) for the suction flow rate. Figure 6 shows the results at 35 deg for $\alpha^+ = 0.072$ and a Reynolds number range of 30,000–88,000. In this case, the dynamic-stall vortex was completely suppressed by removing fluid at a rate of 0.109 for a range of Reynolds numbers 30,000–50,000. For the same removal rate, however, the flowfield over the airfoil suction surface shows a degraded effect of suction as the freestream velocity increases beyond this value. This effect is first seen at a Reynolds number of 53,000, where the dynamic-stall vortex starts developing near the airfoil leading edge. With increase in freestream velocity, the effect grows, and the ability to suppress the DSV decreases. At a Reynolds number of 88,000, the DSV extends up to trailing edge of the airfoil.

The behavior at lower pitch rates is related to early breakdown of the shear layer.[7] At lower pitch rates, the flow is closer to quasisteady in nature. With the increase in the freestream velocity beyond a critical value, transition to turbulence in the shear layer alters the flow behavior. Since the dynamic-stall vortex is weaker at lower pitch rates, transition and turbulence in the shear layer affect the flow development at comparatively smaller values of Reynolds number. On the other hand, at higher pitch rates, unsteady effects are more dominant, the dynamic-stall vortex is stronger, and the effects of transition and turbulence in the shear layer on the development of the DSV are important only at relatively higher Reynolds numbers. Once a breakdown of the shear layer occurs, the reverse-flow region becomes substantially thicker, and a larger amount of fluid needs to be removed by suction to achieve complete suppression of the DSV. This amount then needs to be increased as the freestream velocity increases.

Flow-visualization records and corresponding suction flow rate measurements reveal that as long as the unsteady flowfield is not influenced by transition and turbulence in the shear layer, control of the DSV is independent of freestream velocity (or Reynolds number). The magnitude of the favorable, streamwise pressure gradient on the suction surface increases with pitch rate and has a highly stabilizing effect on the boundary layer. This causes the shear layer and reverse-flow regions to remain thin and moves transition to higher Reynolds number. Thus, as the unsteady effect increases, the rate of accumulation of reverse-flowing fluid for a given pitch rate is the same for a wider range of Reynolds number.

In summary, the pitch rate has the primary influence on the unsteady flow behavior and dictates the suction flow rate needed to achieve optimal control at a given angle of attack. As long as the reverse-flow region remains thin, the flow can be controlled by removing a small amount of fluid to prevent accumulation in the near-leading-edge region, and the amount of fluid removed is independent of the outer flow velocity. As the pitch rate decreases, the Reynolds number at which transition to turbulence occurs in the shear layer decreases, the flow structure is altered, and the height of the reverse-flow region increases at the same angle of attack.

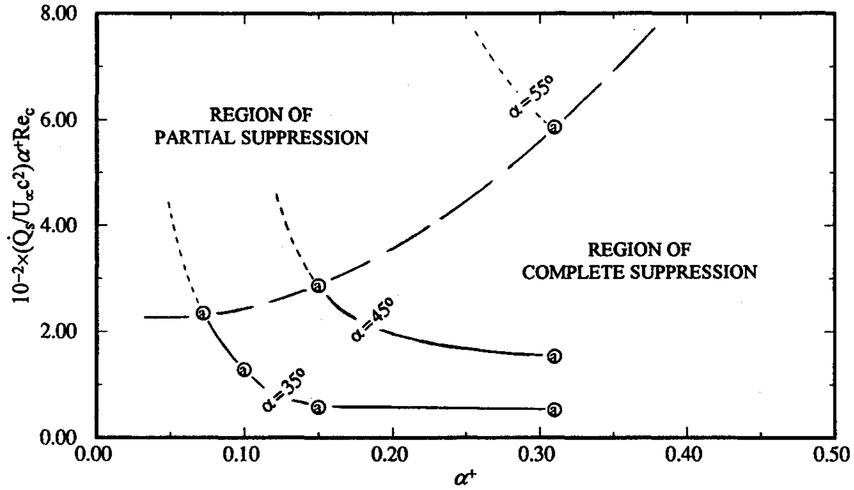

Fig. 7 **Variation of suction flow rate for complete suppression of the DSV with pitch rate, at different angles of attack during the airfoil pitchup.**

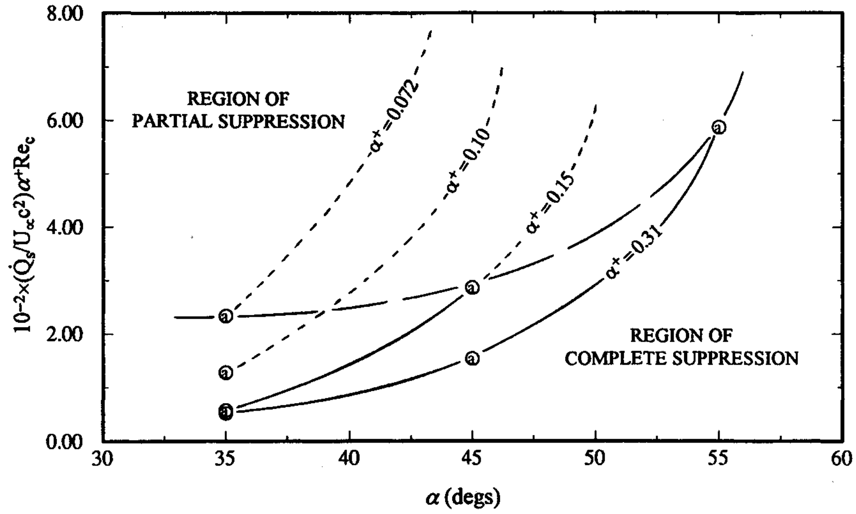

Fig. 8 **Variation of suction flow rate for complete suppression of the DSV with angle of attack, for different pitch rates.**

Flow control now depends not only on the pitch rate but also on the outer velocity (or Reynolds number).

Data were acquired for a few different angles during the pitchup of the airfoil. The flow rates needed for complete suppression of the vortex are plotted against the dimensionless pitch rates in Fig. 7. This representation of the data is useful to study the effect of pitch rate on the control of the dynamic-stall vortex and to provide evidence for the validity of the simplified model of the accumulation process. The suction flow rate is normalized as $(\dot{Q}_s/U_\infty c^2)\, \alpha^+ Re_c$, using the scaling developed with the model. For a given angle of attack (e.g., 35 deg), this product remains constant for a range of dimensionless pitch rates, as predicted by the model. The extent of this range of α^+ increases as the angle of attack decreases. As the pitch rate decreases for a given angle of attack, the model eventually breaks down, and the amount of suction required starts to increase. At some point, the volumetric rate limit of the suction apparatus used in the experiments is reached. Beyond this, only partial suppression of the DSV is possible, i.e., the control objective is not met. The range of pitch rates where partial suppression was obtained is shown by a broken line on the plot for each angle of attack. Thus, it is possible to define a zone of complete suppression in this parameter space (shown in the figure by a broken line). An increased suction flow rate is required to achieve optimal control as the pitch rate decreases and the airfoil angle of attack increases.

The suction requirements are shown plotted vs angle of attack in Fig. 8 for different dimensionless pitch rates. As the angle of attack decreases and pitch rate increases, the suction required for control decreases. Following a line of constant α^+, it is possible to determine the suction requirements during a constant pitch rate maneuver. To meet the control objective (complete suppression), the suction flow rate needs to be increased as the angle of attack increases. A broken line once again divides the regions of complete and partial suppression. As the pitch rate increases, complete suppression can be achieved at higher angle of attack for the same suction flow rate. The region above the broken line shows the domain where the DSV can only be partially suppressed, and the effectiveness of control degrades as the Reynolds number increases.

The plots in Fig. 9 show the variation of suction flow rate with Reynolds number at two fixed angles of attack for different pitch rates. The range of the Reynolds number where suction control is independent of freestream velocity (Reynolds number) becomes smaller as the pitch rate decreases or angle of attack increases.

Thus, the experiments establish a range of applicability for the proposed scaling, verify the validity of a simple model for the accumulation of reverse-flow fluid, and provide the ability to predict the amount of suction required for complete suppression of the DSV over a domain of the primary parameters that influence the process.

Effect of Suction Activation and Deactivation Time

To examine the influence of suction activation time α_{on} on the control process, flow-visualization records were obtained at 35-deg angle of attack while airfoil was pitching from 0 to 40 deg, for a range of α_{on} with α_{off} fixed at 38 deg. The rate of suction was fixed at the optimum value of 0.0127 for the flow conditions ($\alpha^+ = 0.15$ and $\alpha = 35$ deg). The flow development over the airfoil suction surface for α_{on} values of 6, 10, 15, 20, 25, and 30 deg is compared with the natural case (no suction) in Fig. 10. Suction can be used to suppress the dynamic-stall vortex completely if activated before the airfoil reaches 20 deg (i.e., $\alpha_{on} < 20$ deg). Note that shear layer liftup occurs at about 18 deg for this pitch rate (Fig. 2).

The effect of suction deactivation time on the flow control was examined by fixing α_{on} at 6 deg and varying α_{off} over a range for the same flow conditions. The results indicate that termination of

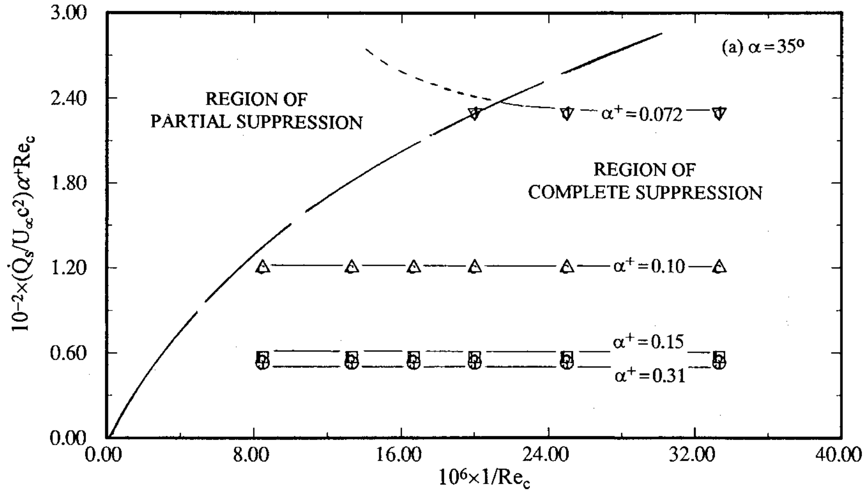

Fig. 9a Variation of suction flow rate for complete suppression of the DSV with Reynolds number, for different pitch rates, α = 35 deg.

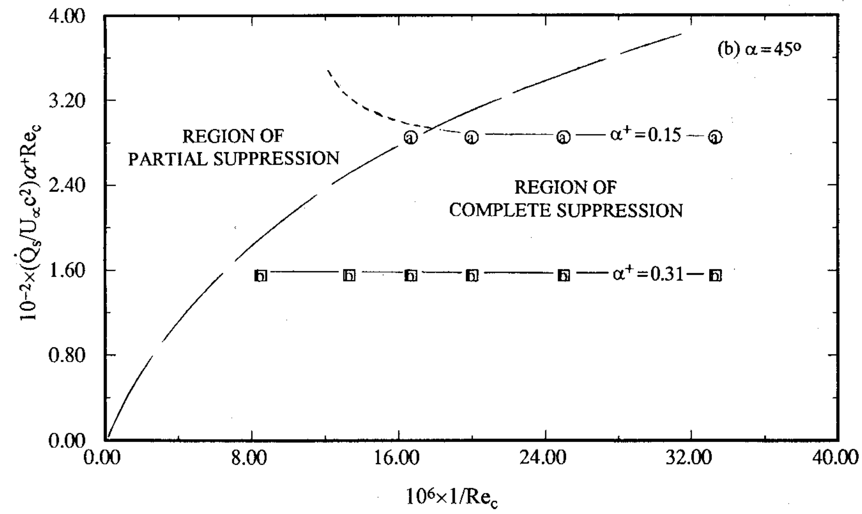

Fig. 9b Variation of suction flow rate for complete suppression of the DSV with Reynolds number, for different pitch rates, α = 45 deg.

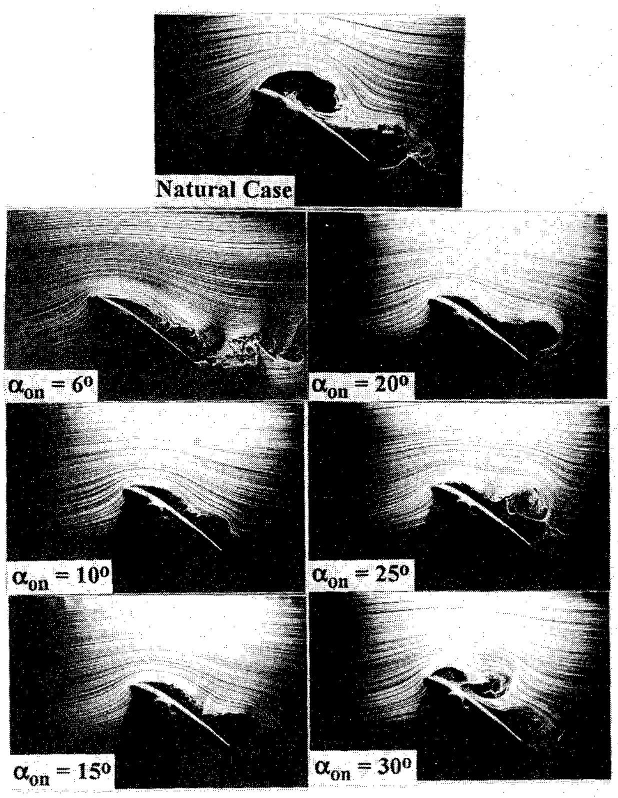

Fig. 10 Effect of suction activation time on flow development during airfoil pitchup; $\alpha^+ = 0.15$, $Re_c = 30{,}000$, $Q_{\mathrm{nd}} = 0.0127$, $\alpha = 35$ deg, and $\alpha_{\mathrm{off}} = 38$ deg.

suction control before the angle of attack at which control is needed results in incomplete suppression of the vortex. This behavior of the unsteady flow suggests that once the suction is initiated, it must be applied continuously, as long as the control is desired. Terminating suction control results in the immediate formation of the dynamic-stall vortex.

Complete suppression of the dynamic-stall vortex therefore requires that two conditions on the suction timing be satisfied: 1) suction activation should be prior to the angle at which the shear layer liftup occurs and 2) suction control should be continued as long as control is desired. However, the selection of the suction flow rate depends on the maximum angle at which the flow control is desired and on the rate at which the airfoil is pitching.

Effect of Width and Position of the Suction Slot

The suction slot width was varied by a factor of four and the slot location changed from 2 to 5% chord. Figure 11 shows two visualizations of the flow at 35-deg angle of attack for $Re_c = 30{,}000$, $\alpha^+ = 0.15$, and slot widths of 0.5 and 2 mm, respectively. In both cases the suction slot was located at 2% of the airfoil chord. These pictures show no significant difference in the flowfield. All of the measurements made indicate that the volume rate of suction, not the suction velocity, is the important control parameter.

Experiments were conducted for slot locations between 2 and 5% of airfoil chord for the same flow conditions as previously described. No significant differences were observed over this range of slot location. It is argued that the slot location is not critical, as long as it is in a region where reverse-flowing fluid can be removed.

Magnitude of Suction

To assess the control technique, some measure of the energy expended in its implementation is needed. The dimensionless suction flow rate Q_{nd} compares the suction flow rate $\dot{Q}_s$ with a representative flux of oncoming fluid $U_\infty c^2$ and provides a measure to assess the amount of fluid removed. For complete suppression of the DSV over the range of pitch rates, chord Reynolds numbers, and

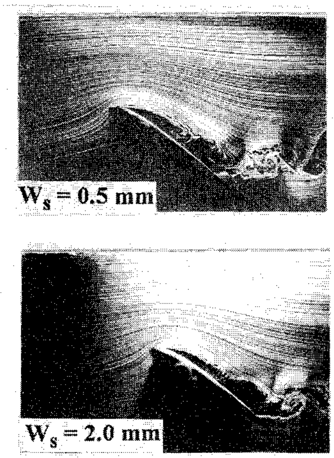

Fig. 11 Effect of suction slot width on suppression of the DSV; slot location 2% chord, $\alpha^+ = 0.15$, $Re_c = 30{,}000$, $Q_{\mathrm{nd}} = 0.0127$, $\alpha = 35$ deg, $\alpha_{\mathrm{on}} = 6$ deg, and $\alpha_{\mathrm{off}} = 38$ deg.

angles of attack examined, the ratio $(\dot{Q}_s/U_\infty c^2)$ was of the order of 0.01. Other control strategies suggested have been suggested, with similar results. Visbal's[6] computations showed that suction with a velocity 4% of the freestream velocity, applied uniformly between the nose and 15% of chord, could suppress the DSV at 36-deg angle of attack at a dimensionless pitch rate of 0.6. When the suction application was concentrated in a region between the nose and 2% of chord, the suction velocity required to suppress the vortex increased to 10% of the freestream velocity. Yang et al.[10] describe control of the DSV using modulated suction and injection at the airfoil surface, over an area that varies with the dimensionless pitch rate. Their computational results show a delay in the onset of dynamic stall, with a corresponding increase in lift and reduction of drag.

Characteristic Length Scale

It is important to note that the events influencing the formation and control of the DSV occur in the leading-edge region of the airfoil and that the mechanisms described can be strongly influenced by the airfoil geometry in this region. Therefore, a length scale characteristic of this region, such as leading-edge radius, is in all probability the appropriate scale to use, rather than the airfoil chord, when describing the Reynolds-number effects. However, since a single airfoil model was used in these studies, the two scales are related by a constant factor, allowing the use of chord Reynolds number in interpreting the results.

Conclusions

These experiments indicate that controlled leading-edge suction can be used in principle as an effective tool to control or modify the dynamic-stall vortex over the suction surface of a two-dimensional, pitching airfoil. The suction required for complete suppression of the vortex depends on pitch rate, airfoil angle of attack, and Reynolds number. Complete suppression is possible over a defined domain of parameter space. The pitch rate is the primary factor that determines suction requirements. The Reynolds number becomes an increasingly important factor as the pitch rate decreases, and transition to turbulence in the shear layer increases the complexity of the flowfield. Under these conditions, the limitations described restrict the use of leading-edge suction for a complete suppression of the DSV. However, when the objective of flow control is partial suppression, leading-edge suction can be used effectively over a wider domain of parameters. This may be a useful approach, for instance, to delay detachment of a formed DSV. Since the formation of the DSV results in increased lift, a delay in the detachment of the DSV could be utilized to get increased lift for a longer period of time and to push the occurrence of dynamic stall to higher angles of attack. Metwally[4] showed that for one set of conditions he examined, suction control delayed the events in the

DSV formation and detachment by 40% of the pitchup period relative to the natural case.

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