Selective Suction for Controlling Bursting Events in a Boundary Layer

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Continuous and intermittent suction from a single streamwise slot was used to eliminate either a single burst-like event or a periodic train of artificially generated bursts in laminar and turbulent boundary layers. The experiments were conducted using a flat plate towed in an 18-m water channel. Flow visualization and hot-film probe measurements were used together with a burst detection algorithm to demonstrate the feasibility of controlling bursting events in a boundary layer. When the suction parameters were optimized, equivalent values of the suction coefficient as low as 0.0006–0.0015 were sufficient to eliminate the artificially generated hairpin vortices.

Nomenclature

C_q	= suction coefficient, V_w/U_0
t	= time, s
U	= streamwise velocity
U_0	= reference velocity
U_∞	= freestream velocity
$U(y)$	= normal velocity profile
$U(z)$	= velocity profile in the spanwise direction
u'	= rms streamwise velocity fluctuations
u_τ	= friction velocity
$-\overline{uv}$	= turbulent shear stress
V_w	= average normal velocity at the wall
x,y,z	= Cartesian coordinates fixed with the plate
y^+	= normal distance from the plate's surface in wall units
Δz^+	= spanwise distance between two holes in wall units
δ	= boundary-layer thickness
θ'	= rms temperature fluctuations
ν	= kinematic viscosity
ν/u_τ	= viscous scale

Introduction

RECENT turbulent boundary-layer research has shown clearly that the wall region is dominated by a sequence of eddy motions that are collectively called the bursting phenomenon. It is realized that, in two-dimensional bounded shear flows, the tangential Reynolds stress is responsible for transferring energy from the mean flow into the turbulence. The studies of Lu and Willmarth[1] and Blackwelder and Kaplan[2] have shown that most of the tangential Reynolds stress carried by the turbulent flow is associated with the bursting process. Kline et al.[3] indicated that the Reynolds stress was primarily produced by the ejection of low-speed streaks from the wall region. Thus, if these events could be inhibited, the Reynolds stress would be decreased, and the turbulence production would be interrupted.

The present experiment was designed to test the feasibility of this idea in a model flowfield. In a real flow, the locations of the low-speed streaks are not known a priori. Thus, artificial streaks were generated in a laminar or turbulent boundary layer with a zero pressure gradient. After the low-speed streak had developed downstream, fluid was withdrawn through a streamwise suction slot to inhibit the ejection process. Since ejections are intermittent, the suction need not be continuous; consequently, both continuous and intermittent suction were used.

An alternative technique that conceivably could reduce the Reynolds stress and reduce the drag is to inject fluid selectively under the high-speed regions. The immediate effect would be to decrease the viscous shear at the wall resulting in less drag. In addition, the velocity profiles in the spanwise direction, $U(z)$ would have a smaller shear $\partial U/\partial z$ because the injection would create a more uniform flow in the spanwise direction. Since Swearingen and Blackwelder[4] have found that inflectional $U(z)$ profiles occur as often as inflection points are observed in $U(y)$ profiles, injection under the high-speed regions would decrease this shear and hence the resulting instability.

The combination of selective suction and injection is sketched in Fig. 1. In Fig. 1a, the vortices are idealized by a periodic distribution in the spanwise direction. The instantaneous velocity profiles without suction and injection at constant y and z locations are shown by the dashed lines in Figs. 1b and 1c, respectively. Clearly, the $U(y_0,z)$ profile is inflectional, having two inflectional points per wavelength. At z_1 and z_3, an inflectional $U(y)$ profile is also evident. The same profiles with suction at z_1 and z_3 and injection at z_2 are shown by the solid lines. In all cases, the shear associated with the inflection points should be reduced. Since the inflectional profiles are all inviscidly unstable with growth rates proportional to the shear, the resulting instabilities would be weakened by the suction/injection process. Because the turbulent shear stress, $-\overline{uv}$ may result from the inflectional instability, it also should be reduced.

The only prior research using selective suction was due to Wilkinson et al.,[5] who applied continuous suction along the troughs of a longitudinally ribbed surface having a spanwise wavelength in the range of 5–20 ν/u_T and modeled after the riblets of Walsh.[6,7] Wilkinson et al. achieved zero boundary-layer growth with suction coefficients of $C_q \simeq 0.003$, in agreement with the results of Rotta[8] and Verollet et al.[9] (The suction coefficient is defined by $C_q \equiv V_w/U_0$, where V_w is the average normal velocity at the wall and U_0 the reference velo-

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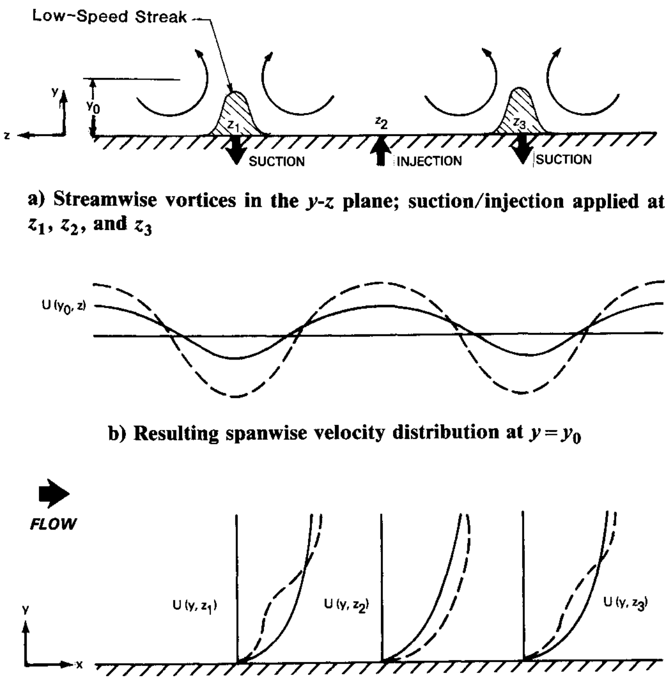


a) Streamwise vortices in the *y-z* plane; suction/injection applied at z_1, z_2, and z_3

b) Resulting spanwise velocity distribution at $y = y_0$

c) Velocity profiles normal to the plate

Fig. 1 Effects of suction/injection on velocity profiles (dashed lines are reference profiles and solid lines are profiles with suction/injection applied).

city, i.e., the freestream velocity for boundary layers.) However, the total drag, consisting of the integrated skin friction and the momentum loss due to suction, increased with C_q, much the same as the uniform suction results reported in Refs. 10 and 11. Wilkinson et al.[5] concluded that the longitudinal slots did not have any advantage over other porous surfaces. There are two possible reasons for their results. First, there is no evidence that the closely spaced riblets they used interacted with the low-speed streaks directly. However, with a larger spanwise spacing ($\sim 100\ \nu/u_\tau$), Johansen and Smith[12] have shown that longitudinal roughness elements with a smaller dimension normal to the wall effectively held the low-speed streaks directly above them. Second, to alleviate the magnitude of the inflectional velocity profiles associated with the low-speed streaks, the suction should be applied to the low-speed regions directly. The suction slots of Wilkinson et al. do not appear to have had the appropriate geometry necessary to have altered the low-speed streaks selectively.

The only research on the details of the wall region in the presence of suction seems to be that of Eléna.[13] He made measurements of u' and θ' in the heated wall region of a large-diameter turbulent pipe flow with and without suction for suction coefficients of $0 \leq C_q \leq 0.003$. He found that the maximum u' turbulence level at $y^+ \simeq 13$ dropped from 15–12% as C_q varied from 0–0.003. More dramatically, the tangential Reynolds stress dropped by a factor of 2 for the same variation of C_q. The dissipation length scale near the wall increased by 40% and the integral length scale by 25% with the suction.

Eléna[13] reported some measurements of the instantaneous velocity and temperature signals with and without suction. He found that the suction decreased the magnitude of both the temperature and velocity fluctuations and increased the time interval between large-amplitude fluctuations. The suction especially decreased the negative velocity excursions at $y^+ < 30$. These results are consistent with the idea that the suction primarily affects the low-speed streaks by reducing their magnitude and thus inhibiting their ability to participate in the production of turbulent energy.

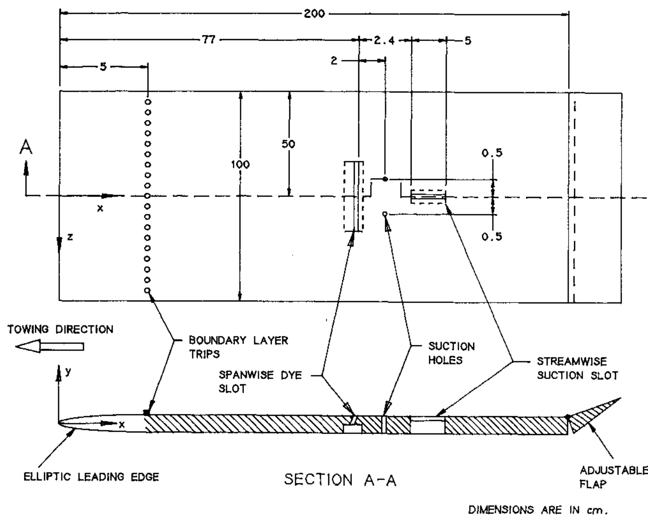


Fig. 2 Schematic of the flat plate (not to scale).

Experimental Approach

Turbulent and laminar boundary layers were generated by towing a flat plate in a water channel 18 m long, 1.2 m wide, and 0.9 m deep. The towing tank has been described in Ref. 14. The flat plate was rigidly mounted under a carriage that rides on two tracks mounted on top of the tank. During towing, the carriage was supported by an oil film to ensure a vibrationless tow, having an equivalent freestream turbulence of about 0.1%. Most of the runs reported here were conducted at a speed of 20 cm/s.

A unique, zero-pressure-gradient flat plate was constructed for the present investigation. The 1×2 m structure was made of glass-reinforced polycarbonate plate 6 mm thick, glued to a stainless steel frame designed for minimum obstruction to the flow. The plate, shown schematically in Fig. 2, had an elliptic nose at the leading edge and an adjustable lifting flap at the trailing edge. To avoid leading-edge separation and premature transition on the upper working surface, the flap was adjusted to a negative attack angle of 10 deg so that the stagnation line near the leading edge was located on the working surface of the plate. The plate was flat to within a few microns, making it one of the most controlled test beds available for boundary-layer research. A laminar boundary layer could be obtained over the entire working surface for towing speeds in the range of 5–80 cm/s. Trips were used to generate a fully developed turbulent boundary layer with a low Reynolds number. The trips were brass cylinders 3.2 mm in diameter and 2.5 mm high placed 50 mm downstream of the leading edge and had their axes perpendicular to the flat plate with a center-to-center distance of 50 mm.

To generate an artificial burst, the excitation technique described by Gad-el-Hak and Hussain[15] was used. Suction was applied impulsively or continuously through two holes separated in the spanwise direction by a distance of 10 mm ($\Delta z^+ \simeq 100$). The minute holes were 0.4 mm ($\simeq 4\ \nu/u_\tau$) in diameter and were connected to a low-pressure chamber controlled with a solenoid valve that was driven by a signal generator. This allowed the sudden withdrawal of a given amount of fluid and the generation of a horseshoe vortex that evolved into a burst. The burst generator was located 790 mm downstream of the plate's leading edge.

A single streamwise slot mounted flush with the flat plate was used to withdraw selectively the near-wall fluid in the boundary layer. The slot was located just behind the artificial burst generator at $x = 794$ mm and had a width of 0.1 mm ($\simeq 1\ \nu/u_\tau$) and a length of 50 mm ($\simeq 500\ \nu/u_\tau$). The lateral position of the slot was chosen to correspond to the location of the artificially generated low-speed streaks. An internal reservoir directly underneath the streamwise slot ensured that the flow

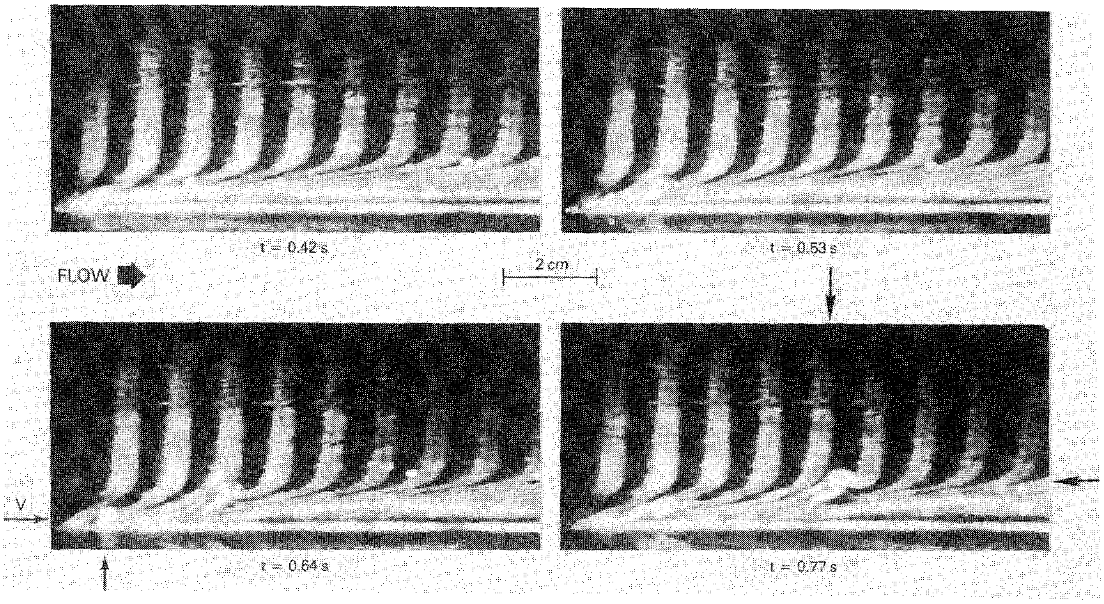


Fig. 3 Side view of the laminar boundary layer visualized using hydrogen bubbles from a vertical wire (suction from the two spanwise holes is applied for 0.5 s at a rate of 2.3 cm³/s).

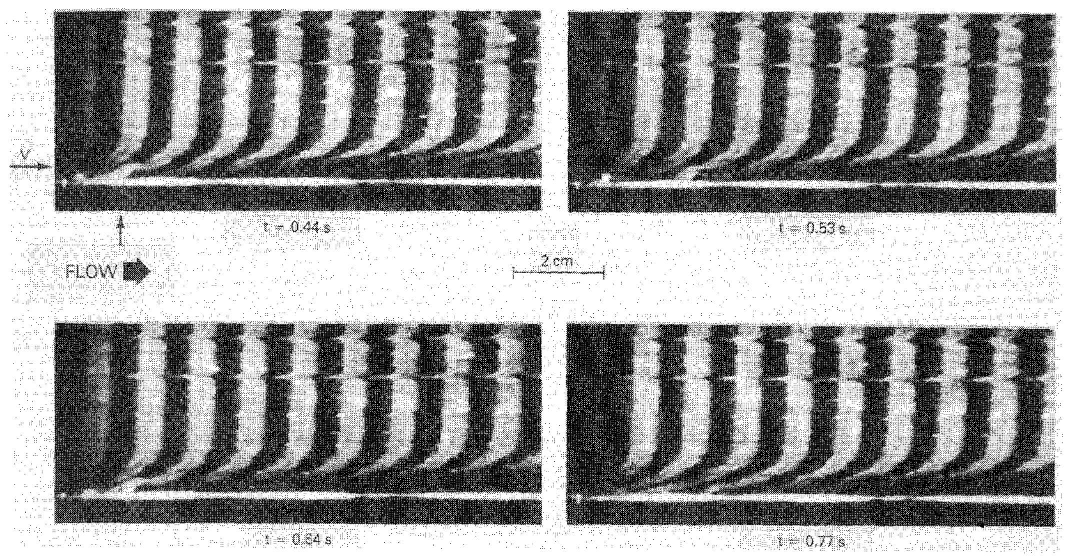


Fig. 4 Burst-like event generated in the laminar boundary layer by withdrawing fluid from two spanwise holes for 0.5 s at a rate of 2.3 cm³/s (the streamwise slot is used to eliminate the resulting hairpin vortices; suction from the slot is continuous at a rate of 4 cm³/s).

rate was uniform to within 5% along the entire length of the slot. A small conduit connected the reservoir to a low-pressure plenum controlled with a solenoid valve driven by a signal generator. This allowed the impulsive or continuous withdrawal of a given amount of fluid from the slot. The phase between the artificial generation of a burst and the withdrawal of near-wall fluid from the streamwise slot was controlled within the limitations of the experimental apparatus.

The amount of fluid withdrawn from the streamwise slot was controlled by changing the suction duration and the pressure inside the low-pressure chamber. In the continuous mode, the flow rate varied between 1 and 10 cm³/s. Since suction was never applied uniformly over the surface, the average normal velocity was used to define the suction coefficient. The average normal velocity was the flow rate divided by the area over which it was applied. The width of the slot was 0.1 mm and its cross-sectional area was 5 mm². Only one slot was necessary for each low-speed streak, and the average spanwise distance between low-speed streaks in the flow was 10 mm ($100\ \nu/u_\tau$). Thus, the effective area over which the suction was applied was 500 mm², which yielded an equivalent average normal velocity of 0.2–2 cm/s; i.e., this velocity applied uniformly over the plate would remove the same amount of fluid. The corresponding values of the suction coefficient, $C_q = 0.01$–0.1, are large compared with previous suction results;[10,11,13] however, further reductions should be possible by optimizing the geometry of the suction slot. For example, increasing the width of the slot to more closely correspond to the width of the low-speed streaks, i.e., $20\ \nu/u_\tau$, would reduce the normal velocities and apply more of a perturbation to the streak. Moreover, as seen in the next section, intermittent suction reduced the equivalent average normal velocity considerably.

To visualize the near-wall events in the laminar and turbulent boundary layers, both fluorescent dye and hydrogen-bubble techniques were used. The dyes were seeped into the bounday layer through a spanwise slot 0.15 mm ($\simeq 1.5\ \nu/u_\tau$) wide and 150 mm long and located 770 mm downstream of the

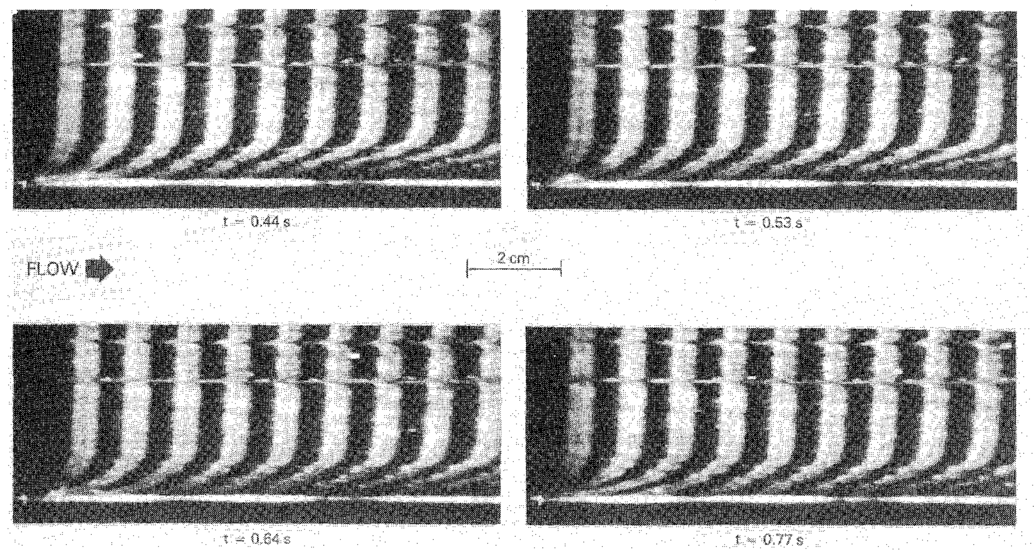


Fig. 5 Higher suction rate from the streamwise slot is more effective in eliminating the hairpin vortices (continuous suction from the slot is at a rate of 5.5 cm^3/s).

leading edge of the flat plate. The dye slot was milled at a 45 deg angle inclined toward the plate's trailing edge to minimize the flow disturbance.

The hydrogen bubbles were generated using a stainless steel wire having a diameter of 0.05 mm and a length of 100 mm. The wire was placed at different locations either parallel to or perpendicular to the flat plate to obtain top or side views, respectively, of the flowfield. To create time lines, a standard circuit was employed to supply intermittenly 100 V to the wire, which acted as a cathode.

Both the fluorescent dyes and the hydrogen bubbles were illuminated using sheets of laser light projected in the desired plane. This provided an extra degree of freedom in observing the large-eddy structures and the bursting events because both the tracer and the light location could be controlled within the limitations of the experimental apparatus. To generate a sheet of light, a 5 W argon-ion laser (Spectra Physics model 164) was used with a mirror mounted on an optical scanner having a natural frequency of 720 Hz (General Scanning, Inc.) and driven by a sine-wave signal generator of the desired frequency. The frequency of the sine wave usually was set equal to the inverse of the shutter speed of the camera. The light sheets were approximately 1 mm thick, which was sufficient to resolve most organized motions within the turbulent regions. A vertical sheet of laser light parallel to the flow was used to visualize side views of the wall events and large-eddy structures, and a horizontal sheet near the surface of the plate was used to obtain top views of the flowfield in the vicinity of the wall.

Miniature boundary-layer hot-film probes (TSI model 1260) together with a 10-channel constant-temperature anemometer (TSI model 10538) were used in the present investigation to measure the longitudinal mean and fluctuating velocities. The probe diameters were 0.025 mm, and their sensing lengths were 0.25 mm. A probe traverse powered by a stepping motor and controlled through an Apple II microcomputer was used for surveying the boundary layers.

The purpose of the present phase of the investigation was to determine the effectiveness of the selective suction on a single bursting event or a periodic train of artificially generated bursts in laminar and turbulent boundary layers. The algorithm employed in the case of a turbulent flow was a burst detection scheme using the variable-interval time-averaging (VITA) technique.[2] A single hot-film probe located at $y^+ = 20$ was used for detecting both the natural and artificial bursting events. The program counted the number of bursts that occur near the wall and recorded their intensities.

Selective Suction in Laminar Boundary-Layer Flows

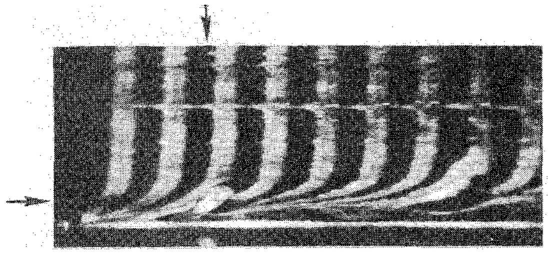
Visualization Results

The burst-like event generated from the two spanwise holes can be eliminated by withdrawing the fluid from the streamwise slot either impulsively or continuously. In Fig. 3, the suction was applied from the two spanwise holes for 0.5 s at a rate of 2.3 cm^3/s. The hydrogen-bubble wire was located between the two holes, and the time in seconds was indicated from the initiation of the suction. A hairpin vortex was generated at the beginning and termination of the suction. In Fig. 3, the initial vortex is denoted by the arrows at $t = 0.77$ s and the second smaller vortex is indicated at $t = 0.64$ s. Neither of these vortices were observed to burst in the visualized domain. Figure 4 has identical flow conditions with continuous suction from the streamwise slot at a rate of 4 cm^3/s. As shown in the figure, both vortices were nearly eliminated. When the suction rate from the streamwise slot was increased to 5.5 cm^3/s, the two hairpin vortices generated from the holes were completely removed, as shown in Fig. 5.

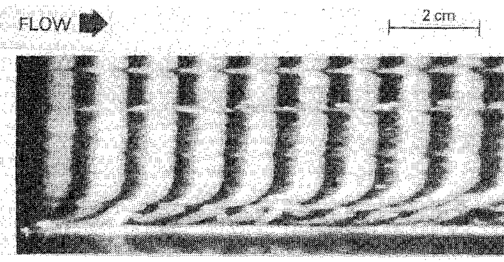
Continuous suction from the two spanwise holes generated a periodic train of hairpin vortices as illustrated by Bradshaw (p. 58 of Ref. 16). This condition is seen in Fig. 6a for a suction rate of 2.35 cm^3/s. In Fig. 6b, continuous suction was applied only from the streamwise slot at a rate of 3 cm^3/s to illustrate that no unsteadiness was apparent in the laminar boundary layer. However, the boundary layer had a fuller profile than the Blasius profile, as seen from the time lines in the figure. When continuous suction was applied from both the two spanwise holes and the single streamwise slot, the periodic train of hairpin vortices disappeared as shown in Figs. 6c and 6d. As expected, the larger suction rate from the slot shown in Fig. 6d (5.5 cm^3/s) was more effective in eliminating the artificial disturbances compared to the more moderate rate of 3 cm^3/s shown in Fig. 6c.

Hot-Film Probe Results

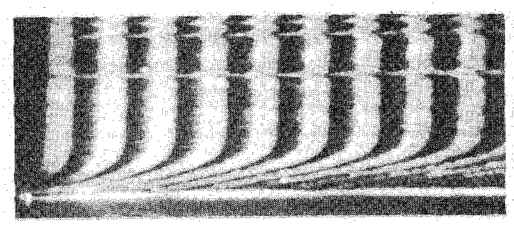
To study more quantitatively the effects of the streamwise suction slot on the burst-like events generated in a laminar boundary layer, hot-film probes were used. A time record of five artificial events is shown in Fig. 7a. The probe was centered behind the two holes and was located at $x = 840$ mm (50 mm or 500 ν/u_τ downstream of the two spanwise holes) and $y = 5$ mm (50 ν/u_τ or 0.49δ), and the freestream velocity was 20 cm/s. Suction was applied from the two spanwise holes for 0.5 s at a rate of 2.3 cm^3/s. A negative spike was observed in the velocity record whenever an artificial event was trig-



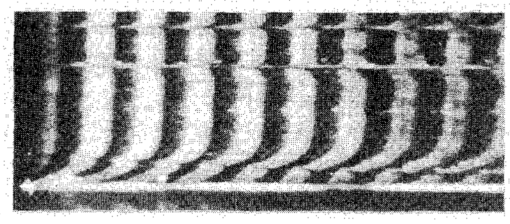
a) Artificial burst-like events generated from two spanwise holes



c) Suction from the streamwise slot at a rate of 3 cm³/s removes some of the instability resulting from the two spanwise holes



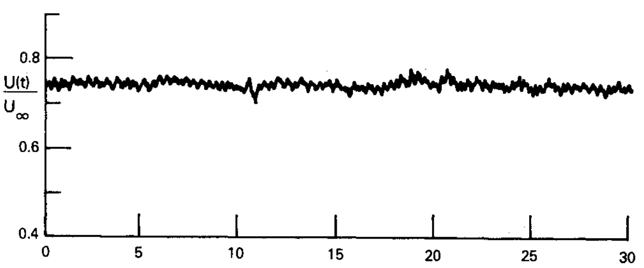
b) Continuous suction from the streamwise slot at a rate of 3 cm³/s has no apparent effect on the laminar boundary layer



d) Increasing the rate of fluid withdrawal to 5.5 cm³/s seems to completely eliminate the resulting instability

Fig. 6 Effects of suction from the streamwise slot on the artificially generated bursts in a laminar boundary layer.

a) Suction from two spanwise holes repeated five times, each lasting 0.5 s at a rate of 2.3 cm³/s



b) In addition to suction from two holes, fluid is withdrawn from the streamwise slot for 0.1 s at a rate of 1.5 cm³/s (suction from slot starts 0.25 s after suction from holes)

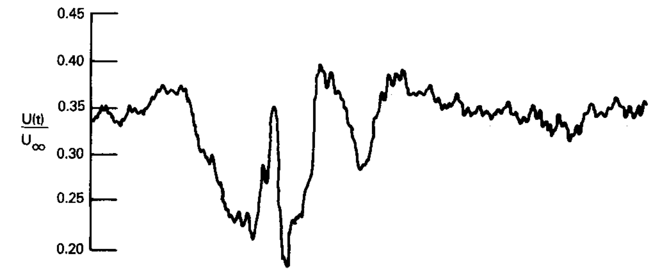
Fig. 7 Effects of suction from streamwise slot on five artificially induced hairpin vortices in a laminar boundary layer ($U_\infty = 20$ cm/s, $x = 840$ mm, $y = 5$ mm).

gered. Note that the second hairpin generated under the conditions seen in Fig. 3 does not appear in the present figure because it was weaker and did not rise to the probe's location. The spike's strength and sign depend on both the probe location and the parameters of the impulsive suction because the hairpin vortex that results from the artificial disturbance evolves differently for different suction rates and duration. In the present example, hairpin vortices were artificially generated, but no bursting occurred at the probe's location at this weak suction rate.

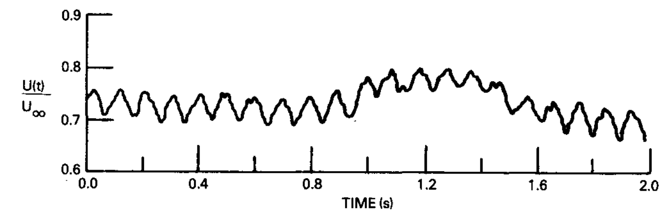
Attempts were made to eliminate these events using impulsive or continuous suction from the streamwise slot. Figure 7b indicates a successful attempt to remove the spikes associated with the vortices shown in Fig. 7a. Suction from the streamwise slot was applied periodically at a rate of 1.5 cm³/s and for a duration of 0.1 s each cycle. The impulsive suction from the slot always started 0.25 s after the onset of suction from the two spanwise holes. The time record shown in Fig. 7b shows no evidence of the artificial events.

The vertical velocity through the streamwise slot was 30 cm/s for the conditions in Fig. 7b. Since the slot width was 1% of the average spanwise streak's spacing, the average continuous normal velocity would have been 0.3 cm/s. However, the suction was applied for only 0.1 s to remove each burst. In a corresponding turbulent boundary layer, this duration would represent 4–10% of the total time. Thus, the equivalent suction coefficient is $0.0006 < C_q < 0.0015$. This equivalent rate is 2–5 times smaller than that reported in Refs. 8 and 9 as the rate of uniform transpiration necessary to yield zero growth of the boundary layer's momentum thickness.

Strong impulsive suction from the two spanwise holes resulted in the generation of a hairpin vortex that burst (broke down into turbulence). This is shown in the time record in Fig. 8a. The hot-film probe was centered behind the two spanwise holes and was located as $x = 820$ mm and $y = 2$ mm ($y/\delta = 0.2$). Suction was applied from the holes for 0.5 s at a rate of 2.8 cm³/s. The resulting fluctuations are different from the single spike associated with a hairpin vortex in Fig. 7a, because the generation suction was increased by 20%, and the velocity signal was obtained at a lower position in the boundary layer. The burst-like event was partially obliterated using continuous suction from the streamwise slot at a rate of 9.4 cm³/s as shown in Fig. 8b. Clearly, this suction rate ($C_q = 0.09$) is too high to be of practical value, and the process must be further optimized by using intermittent suction, etc. Also, the suction rate is so large that distortion of the flowfield may have been present, e.g., the oscillations seen in Fig. 8b. It is clear that a mature burst is more difficult to eliminate than a newly developed hairpin vortex.



a) Single burst-like event generated in a laminar boundary layer (suction from two spanwise holes lasting for 0.5 s at a rate of 2.8 cm^3/s)



b) Continuous suction from the streamwise slot at a rate of 9.4 cm^3/s partially obliterate the burst

Fig. 8 Effects of suction from streamwise slot on a single burst-like event in a laminar boundary layer.

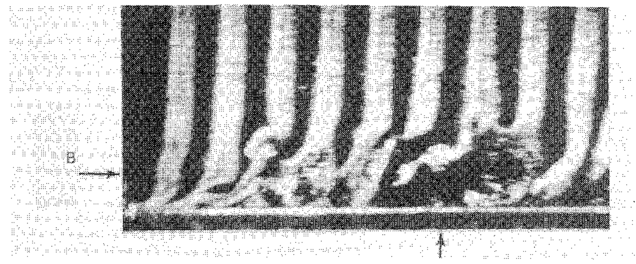
Selective Suction in Turbulent Flow

The ultimate application of the selective suction technique will be to reduce the skin-friction drag in a turbulent boundary layer. The previous section of this paper illustrated the feasibility of the concept in a laminar flow where flow visualization and probe measurements are relatively easy to conduct and interpret. The problem in a turbulent flow is much more complex. The background turbulence fluctuations make it more difficult to visualize or to measure the organized structures that we are attempting to control. Nevertheless, some limited measurements were conducted in a turbulent boundary layer during the present phase of the investigation.

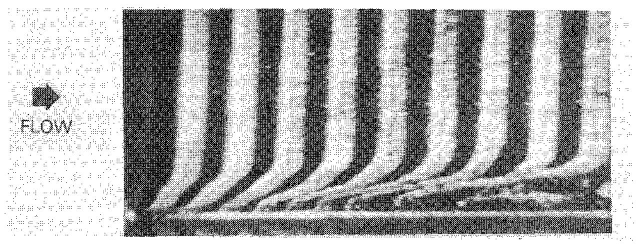
Continuous suction from the streamwise slot was applied in an attempt to reduce the frequency or the strength of bursting events at a given location. This task was not easy and required very careful optimization. A successful attempt is shown in the sequence of photographs in Fig. 9. The towing speed was $U_\infty = 20$ cm/s, and the field of view in each photograph was from $x \simeq 790$–900 mm. In Fig. 9a, a typical photograph in a natural boundary layer during bursting is depicted.[3] Continuous suction from the slot is applied at a rate of 4 cm^3/s, and the effect on natural bursts is shown in Figs. 9b and 9c. The flow seems to be more quiet in this case, although a shear layer appears to develop intermittently (Fig. 9c).

More quantitative information was obtained using hot-film probes and the detection algorithm described earlier. Artificial bursting events were generated in the turbulent boundary layer by withdrawing fluid impulsively from the two spanwise holes, and attempts were made to prevent these events from developing by using either continuous or impulsive suction from the streamwise slot. About 80% of these bursts were eliminated when suction from the slot was applied for 0.1 s at a rate of 4 cm^3/s.

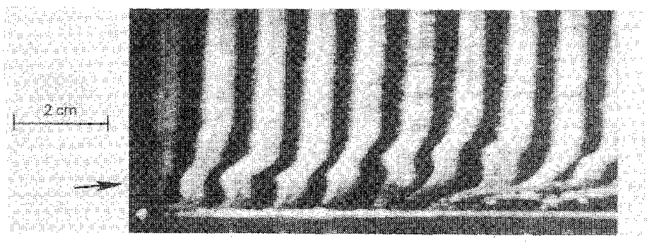
For natural bursts and in the absence of a reliable detector for their onset, continuous suction obviously is needed due to their random occurrence. When continuous suction was applied optimally from the streamwise slot, the natural bursting frequency as computed from the VITA algorithms was reduced by as much as 50%.



a) Natural turbulent boundary layer



b) Continuous suction from slot at a rate of 4 cm^3/s



c) Shear layer appears to develop intermittently when suction is applied from streamwise slot

Fig. 9 Effects of suction from streamwise slot on bursting events in a turbulent boundary layer ($U_\infty = 20$ cm/s).

Summary

The primary objective of the present research was to investigate experimentally the feasibility of removing some or all of the turbulence producing eddy structures in a turbulent boundary layer using the beneficial effects of intermittent suction applied with knowledge of the spatial location of the eddy structure. When optimized, this selective suction technique should require less energy expenditure than continuous, uniform suction.

During the present investigation, the feasibility of the innovation was determined by conducting a set of well-controlled experiments in a zero-pressure-gradient boundary layer using a single streamwise suction slot to eliminate natural and aritificial bursts. Flow visualization and hot-film probe measurements were used together with the VITA detection algorithm. Selective suction from the slot was used to eliminate either a single burst-like event or a periodic train of artificially generated bursts in laminar and turbulent boundary layers. For the given geometry, it was shown that under optimum conditions, values of the suction coefficient as low as $C_q = 0.0006$–0.0015 eliminated the artificially generated low-speed streaks and the accompanying hairpin vortices. This rate is 2–5 times smaller than that reported in other experiments employing transpiration as the rate necessary to yield zero growth of the boundary layer's momentum thickness.

Acknowledgments

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