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AN EXPERIMENTAL EVALUATION OF SLOTS VERSUS POROUS STRIPS FOR LAMINAR-FLOW APPLICATIONS

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INTRODUCTION

Laminar - flow control (LFC) has the potential for significant drag reduction in a wide range of aerodynamic vehicle applications. The primary objective of LFC is the achievement of extended areas of laminar flow by delaying boundary-layer transition where the primary drag reduction benefit is in the decrease in the skin friction. Two competing methods to apply wall suction are the use of discrete slots or a contiguous porous skin along the aerodynamic surface as discussed in (Refs. 1 and 2). The porous surface provides a nearly uniform continuous suction in contrast to a series of narrow slots which provide a discontinuous spatially localized suction distribution.

The estimation of suction quantities for LFC applications can be calculated by assuming continuously applied suction such that the growth factors for instability waves are below a prescribed level. Ref. 3 used boundary-layer theory and showed that if the same amount of suction is distributed at wide porous strips instead of continuous distribution, the integrated amplitudes of Tollmien-Schlichting waves are essentially unchanged. However it would be incorrect to extrapolate this result to the case of localized suction of a slot because the upstream influence of the slot or "sink effect" is not properly accounted for in boundary-layer calculations, which are parabolic in nature. Ref. 4 utilized a triple deck theory to account for the upstream effect and Ref. 5 provided experimental confirmation of these results for wide porous strips. However, the limitations of low wall suction velocities, an inherent assumption of the analytical development, raises a question of the accuracy of this procedure for the case of discrete suction through a series of multiple slots.

The first part of the present study concentrates on a comparative examination of the growth of instability waves in a Blasius boundary-layer flow by these two methods of wall suction. The second part of the paper includes design criteria for suction hardware to minimize velocity perturbations at the entrance of the slot. The slot blockage study demonstrates that a boundary-layer instability develops downstream which may lead to premature transition. The lower limit of this instability for a slot blockage width equivalent to the local boundary-layer displacement thickness represents the most restrictive criteria for the suction rate through a given slot.

EXPERIMENTAL CONFIGURATION

This study was conducted in the Lockheed-Georgia LTWT (Low Turbulence Wind Tunnel) which has a 0.6m X 0.9m rectangular test section by 6.5m length. The free stream turbulence level is of the order .02-.04% of the free stream velocity. The flat plate depicted in Figure 1 has an elliptical leading edge and is constructed of 1.27cm thick aluminum plate with dimensions 0.9m X 3.0m length. Chordwise and spanwise static pressure measurements were made with a total of 32 static surface ports. The pressure gradient was set close to zero over the test region by the adjustment of the tunnel walls with a C_p variation of +0.25%. A variable deflection trailing edge flap attached to the downstream end of the plate controlled the leading edge stagnation line.

Three suction locations were chosen on the flat plate at x=1.22,1.525 and 1.83m from the leading edge. The suction power was provided by a radial vaned pump attached to a vacuum chamber, where the total mass flow was maintained at a constant value by a sonic nozzle at the entrance of the chamber. The flow rate from each panel was controlled by a ball socket valve and monitored by a calibrated pressure drop across a porous membrane installed in each pressure line. To accurately measure the mean flow and the dynamic fluctuations of the instability waves, the boundary-layer surveys were made with a computer driven three-axis probe survey mechanism of resolution .015mm which was mounted outside the test section of the tunnel. The hot wire anemometer used in this study was a Disa type 55D01.

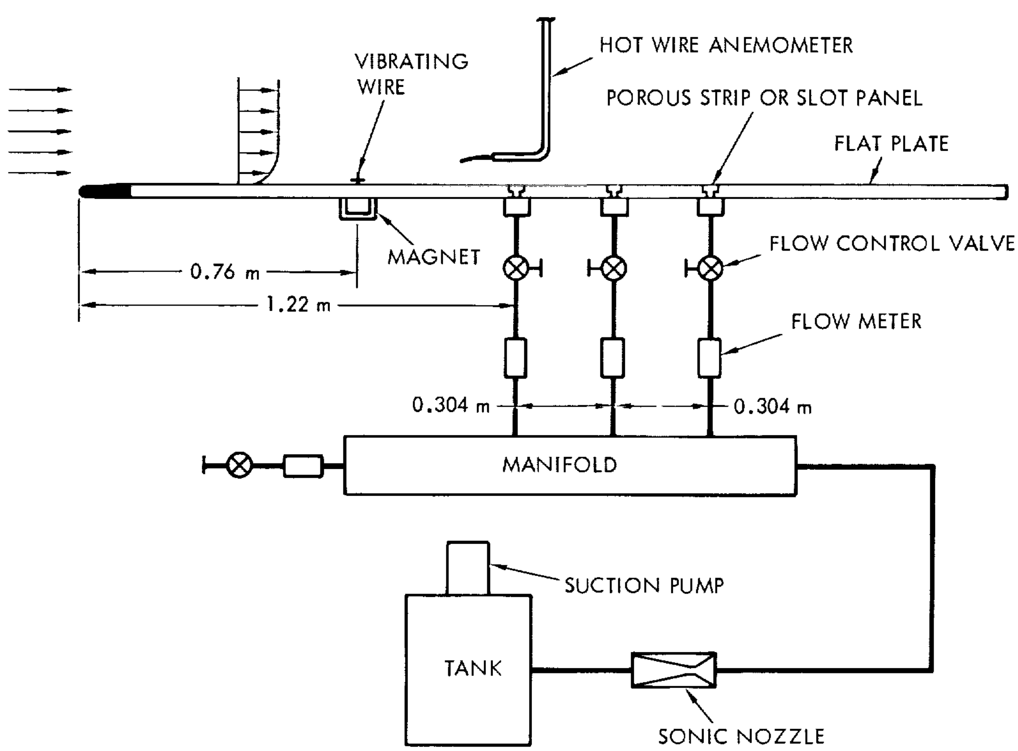


Figure 1

GEOMETRY OF SLOT AND POROUS STRIP PANEL

Figure 2 shows the details of the suction chamber design, where a 2-D slot panel or a wide porous-strip panel was alternately installed above each suction chamber. The porous panels were 2.3cm wide and 10mm thick and contained electron beamed holes of diameter 0.25mm spaced in a diamond pattern with a porosity value of 20% open. The slot panels were the same thickness material with a saw cut of 0.25mm width. A comparison of the slot vs. wide porous-strip data was made by replacing the slot panel with the porous panel without altering the external boundary conditions of the experiment. The slot dimension was 16% of the displacement thickness of the boundary layer as compared to the porous strip width of 15.0 displacement thicknesses. The 0.38cm diameter metering holes were displaced from the centerline of the suction chamber by 0.64cm with a pitch of $75w_s$. The suction chamber had a depth of $21w_s$ and a width of $105w_s$.

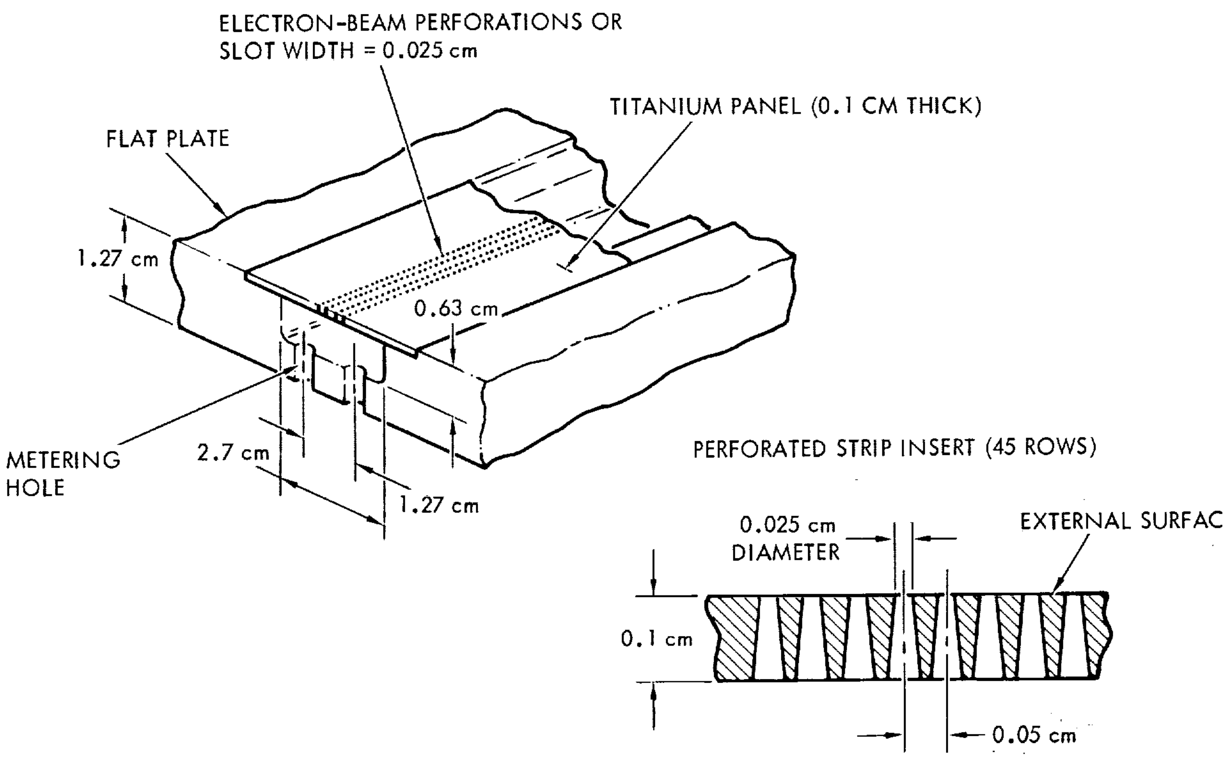


Figure 2

COMPARISON OF MEAN BOUNDARY-LAYER PARAMETERS

From dimensional analysis, with the initial condition specified as a Blasius profile, the change in the mean boundary-layer parameters due to discrete wall suction can be represented by the functional relationship:

$$\delta^*/\theta = g(y_K/\delta^*, w/\delta^*, R_{\delta^*})$$

The first term represents the streamline height of the suction mass flow far upstream of the influence of the wall suction normalized on the displacement thickness, the second term is the non-dimensional width of the wall suction, and the third term is the local Reynolds number. For low suction rates the following expression can be derived for the first term:

$$y_k/\delta^* = 1.88(m)^{1/2}; \quad \text{where } m = wv/U\delta^*.$$

For the data presented in this section $R_{\delta^*} = 2100$, which corresponds to a displacement thickness $\delta^* = 1.65$mm and the unit Reynolds number per meter of R $= 1.336 \times 10^{+6}$. The suction flow was maintained at the same value at each streamwise station during the acquisition of the mean and RMS velocity data. Figure 3a shows the boundary-layer shape factor comparison for slots and porous strips for a suction value of m=.035 at successive downstream locations. The corresponding displacement thickness variation normalized on the reference value is shown in Figure 3b.

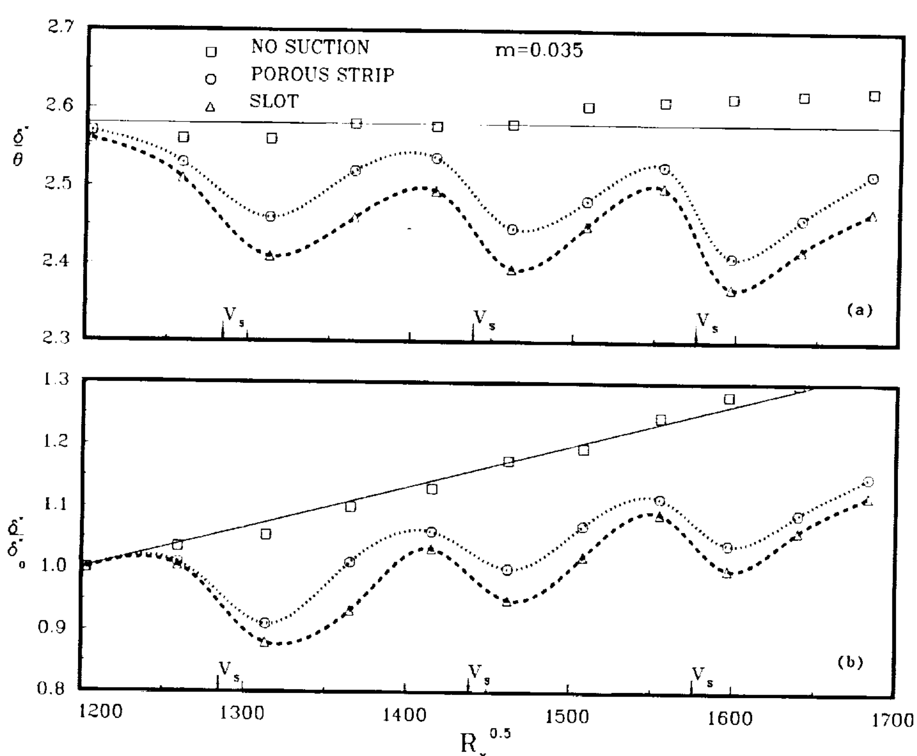


Figure 3

COMPARISON OF LOCALIZED Cp AND SHEAR

The variation of C_p in the near vicinity of the suction region at x=1.22m was measured by a small static probe of diameter $0.2\delta^*$. The comparison of slot vs. wide porous strip is shown in Figure 4a for the suction parameter m=0.035. The main difference in the two suction methods is the higher peak value in C_p of the slot and larger adverse gradient across the slot-suction width. The corresponding skin friction data comparison shown in Figure 4b was obtained from the mean velocity gradient of the anemometer data at a normal distance of 0.15mm from the surface. The significant difference is the larger magnitude of the shear near the downstream edge of the slot.

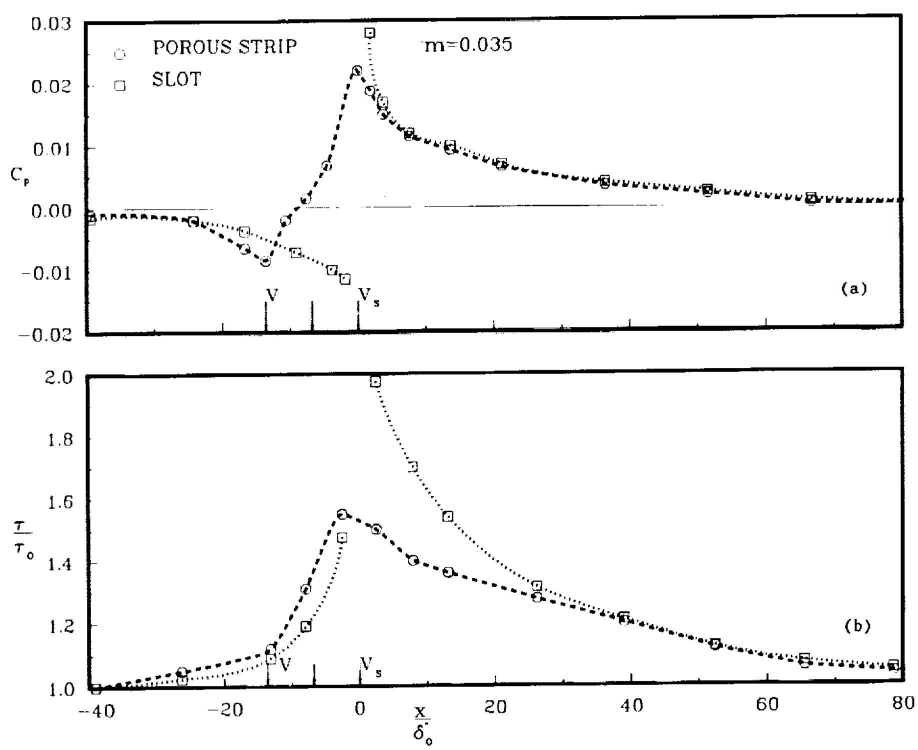


Figure 4

GENERATION OF TOLLMIEN-SCHLICHTING WAVE

The introduction of a controlled disturbance in the boundary layer was accomplished using the vibrating wire technique. An electromagnetically excited stainless-steel wire of diameter 0.025mm was positioned 0.76m from the leading edge and offset from the plate by 0.2mm spacers and allowed to freely vibrate over a length of 0.75m (see Figure 1 previously). A two dimensional array of permanent magnets located underneath the surface provided a constant magnetic field and a power amplifier with a sinusoidal wave generator provided the excitation current for the wire. A weight of 5 Newtons (1.1 lbs) attached to the wire provided the tension force, where the natural frequency of the taught wire was measured at f=210 Hz. This arrangement allowed a constant disturbance amplitude over a spanwise extent of length 0.5m. The measured disturbance wave in the boundary layer is compared to linear stability theory in Figure 5a for a dimensionless frequency of $F=64.4 \times 10^{-6}$. Figure 5b shows the corresponding mean velocity profiles.

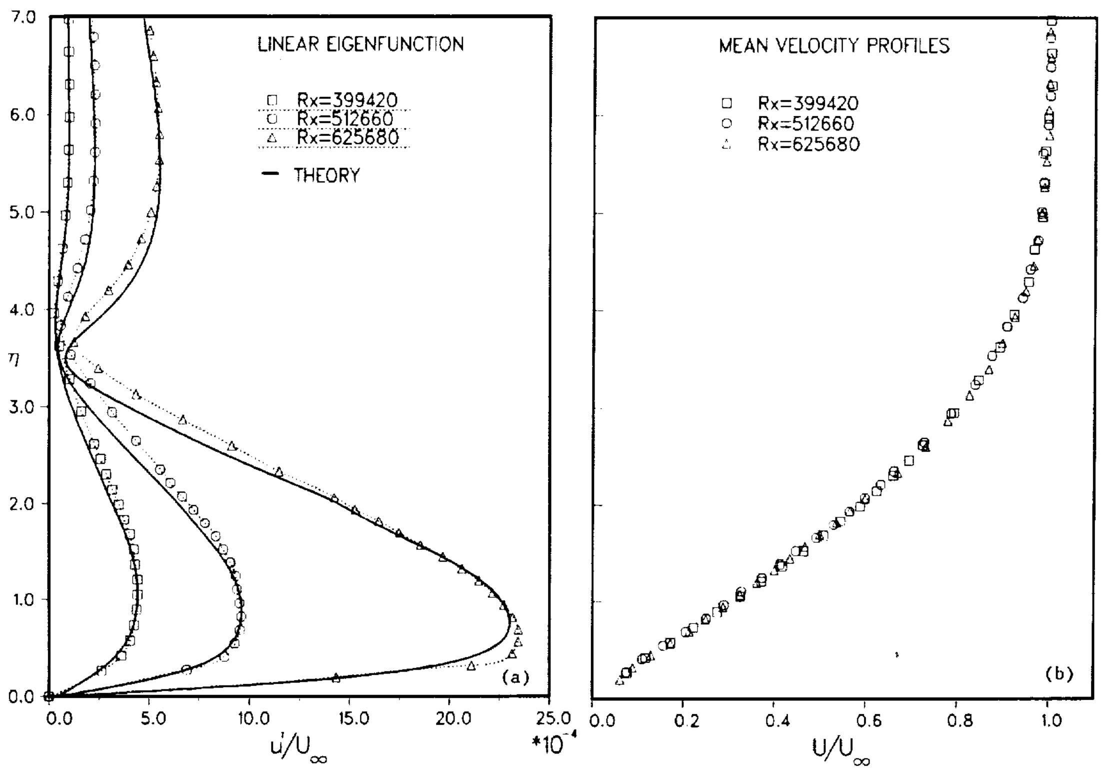


Figure 5

SPECTRAL PLOT OF DELTA FUNCTION VERSUS DISCRETE FREQUENCY

A cursory examination of the frequency which had the largest amplitude growth over the test region was ascertained by the generation of a delta function input to the wave generator at a frequency of 5 Hz. The anemometer was positioned downstream of the last slot at a position in the boundary layer of $y/\delta^* = 0.6$. The spectral plot of the anemometer fluctuations shown in Figure 6a demonstrates a wide band of instability waves were amplified. The suction test experiment was conducted at the relatively low non-dimensional frequency of $F = 28.3 \times 10^{-6}$, which corresponds to the maximum growth of the discrete frequency of the sine wave input at 127 Hz and is shown in Figure 6b. The maximum amplitude of the wave was maintained in the linear range over the test section region for the duration of the experiment.

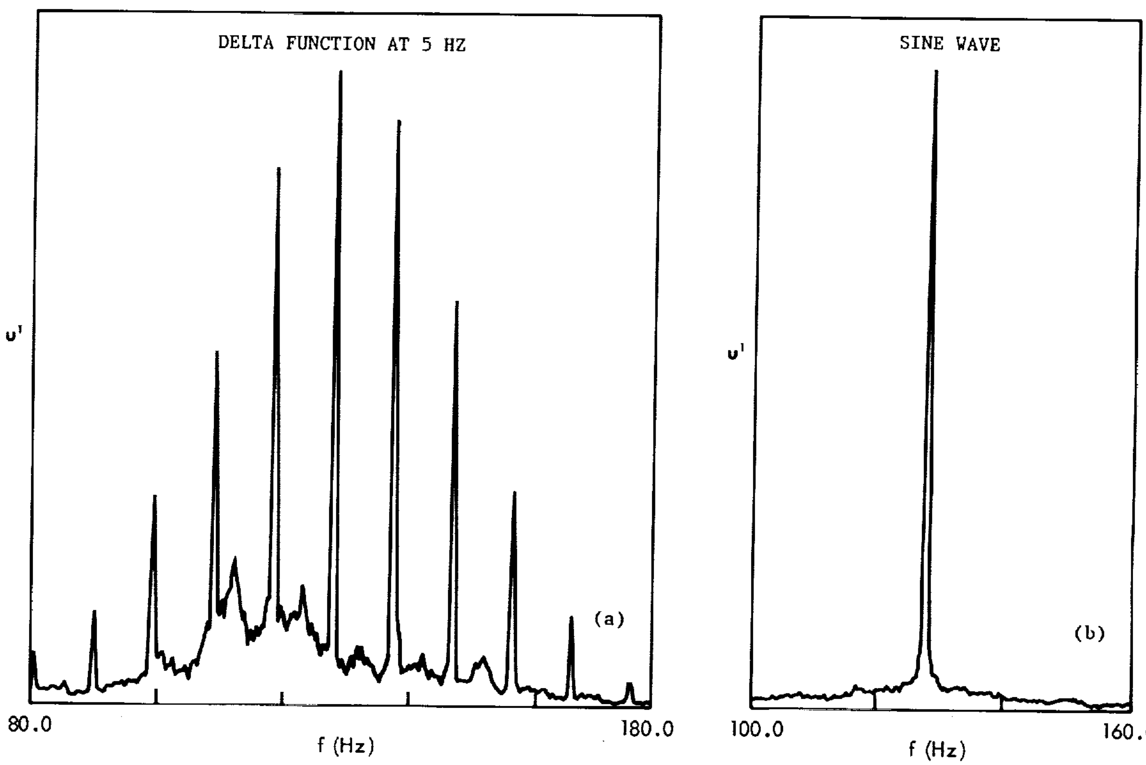


Figure 6

COMPARISON OF AMPLITUDE GROWTH OF INSTABILITY WAVE

The amplitude growth of the instability wave shown in Figure 7 represents a comparison of the porous strip versus slot for two suction quantities. The data in this figure represent the maximum fluctuation amplitude normalized on the maximum amplitude at $(R_x)^{1/2}$ =1200. To demonstrate the effect of suction width on the growth of the instability wave, tape of 0.05mm thickness was used to cover 80% of the width of the porous strip. This configuration had 8 rows of holes which were open on the porous strip panel. Figure 7 shows the amplitude growth for three cases, namely:

a.) wide porous strip of width w/δ^* =15.0
b.) narrow porous strip of width w/δ^* =2.5
c.) and the slot of width w/δ^* =0.16

The effects on stability of the narrow porous strip as compared to the slot are nearly identical.

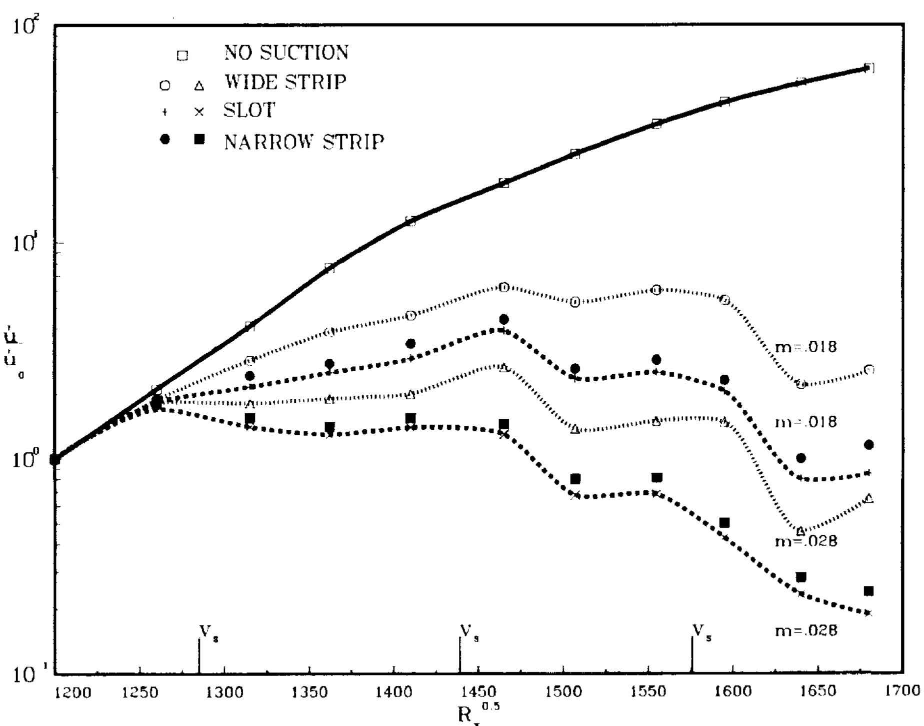


Figure 7

Ref. 6 has demonstrated that premature transition of the boundary layer can occur if there is a breakdown of the internal flow in the suction chamber. Also, an analytical study (Ref. 7) and an experimental study (Ref. 8) have shown nonlinear interactions between three-dimensional and two-dimensional waves which excite exponential growth rates which may lead to premature transition. The amplitude of the three-dimensional waves in which the nonlinear interaction occurs has the low nominal value of $u'/U=0.01\%$. The frequencies where resonance occurs are those which have significant linear growth rates and the corresponding second harmonics and subharmonics. Therefore, from an LFC standpoint it is desirable to minimize the perturbations from the ducting system, since the generation of internal finite disturbances will propagate into the external boundary-layer flow. For this study a closed loop water tunnel was used for both flow visualization and the quantitative data reported in the subsequent sections. The measurements were obtained with a TSI* anemometer using a hot film probe with linearizer, and a Nicholet FFT+ spectrum analyzer was used to obtain the frequency data from the velocity fluctuations. Figure 8a shows the parameters of the slot flow which were investigated, and Figure 8b shows the relationship of the width of the separated region on the parameters R_s and α which are discussed in Ref. 9.

*Thermal Systems Incorporated (TSI).
+fast Fourier transform.

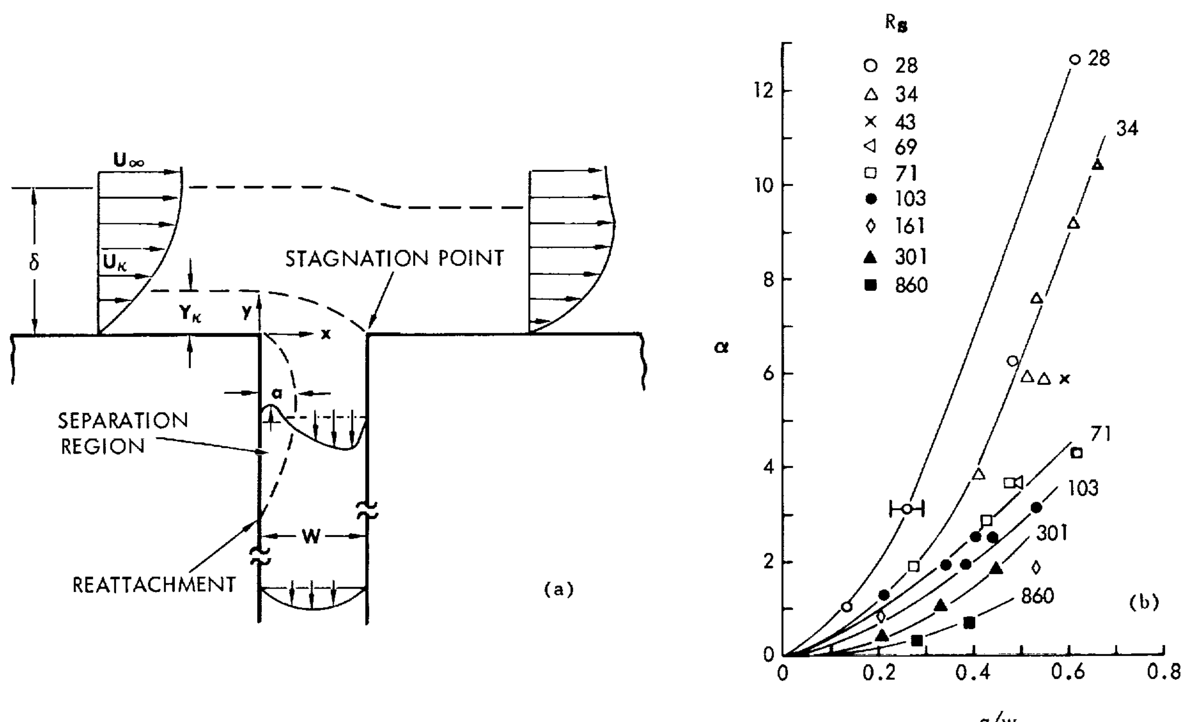
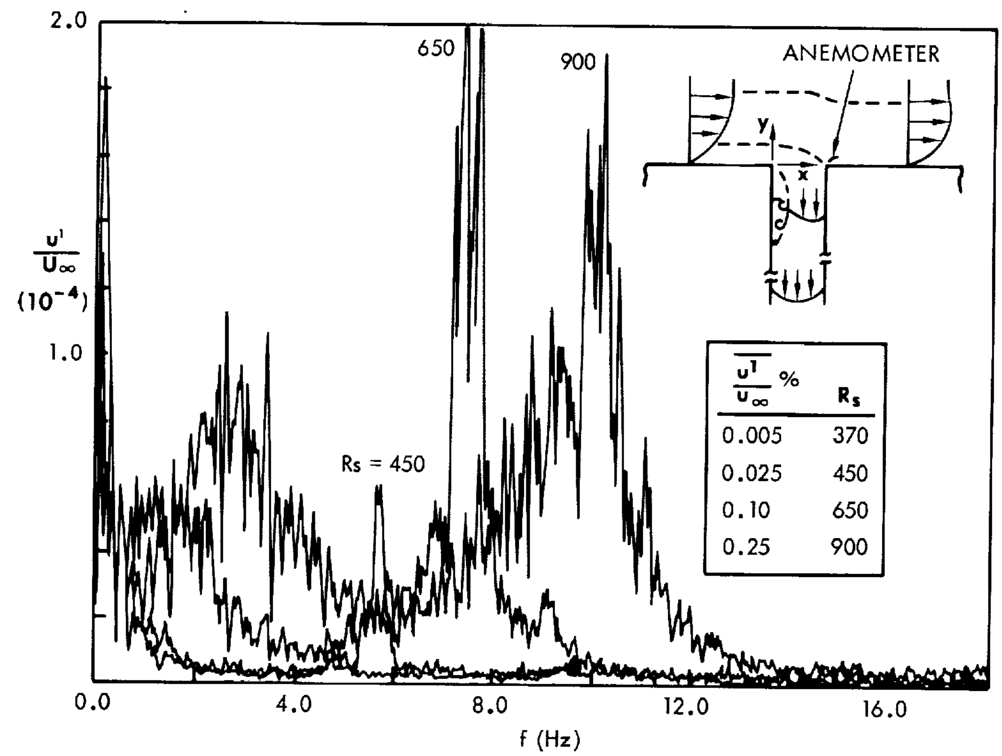


Figure 8

LAMINAR BUBBLE TRANSITION IN SLOT

Flow visualization using dye for a streamline marker demonstrated that the flow separates from the leading edge of the slot and reattaches within 4.0 slot widths depending on the slot Reynolds number and the boundary-layer shear parameter (α) as outlined in Ref. 9. For this experiment the suction chamber was designed with large dimensions to isolate perturbations from the shear layer flow in the slot. Velocity spectra were obtained with a boundary-layer probe located $0.25\delta^*$ downstream of the slot and $0.15\delta^*$ from the surface. The velocity spectra shown in Figure 9 demonstrate that transition and breakdown of the slot laminar bubble occur at a slot Reynolds number R_s =450. The peak in the spectral data collapses to a dimensionless Strouhal frequency fa/v_s =0.038, where the length scale a is the maximum bubble width in the slot.



$\overline{u'}/U_\infty$ %	R_s
0.005	370
0.025	450
0.10	650
0.25	900

Figure 9

SUCTION CHAMBER OSCILLATIONS

Flow visualization using dye markers for the streamlines was used to observe the flow within the chamber below the slot. The two dimensional flow from the slot remains as a coherent jet and impinges on the floor of the duct. The jet then separates into two helical stuctures which are drawn into the metering holes. A study was undertaken to examine the effect of varying the geometry of the suction chamber on the RMS fluctuations at the mouth of the slot with no external boundary-layer flow above the slot. The hot film probe was positioned at the entrance of the slot. The metering holes had a pitch p/w_s=50 with the hole R_d<1200, to minimize pertubations of the flow through the holes. Figure 10 shows the spectral data for three geometries under investigation. The maximum amplitude occurs at a Strouhal frequency S fw/v_s =.0135 where, at higher frequencies, the amplitudes have an exponential decay. The minimum RMS of the oscillations for a given flow rate occurs for a chamber depth = $17w_s$ and chamber width = $40w_s$.

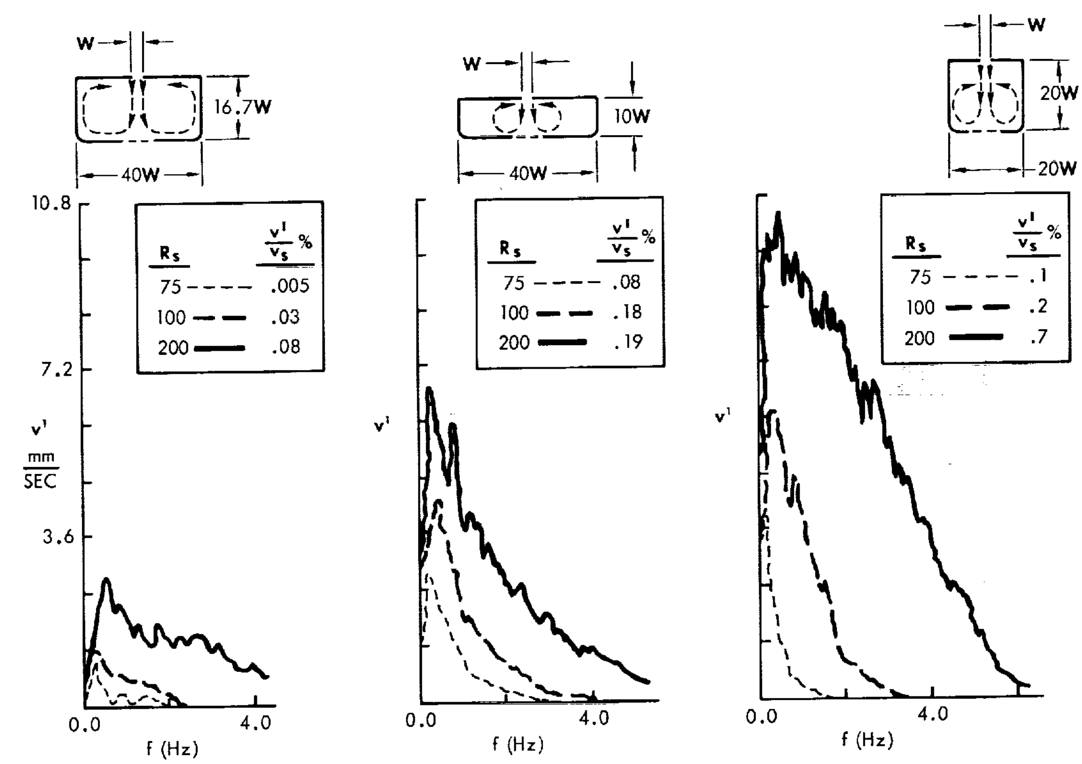


Figure 10

METERING HOLE INSTABILITY

Flow visualization showed that laminar separation of the streamlines occurs at the entrance of sharp-edged holes with reattachment within one diameter. An idealized experiment was studied where a round tube of diameter 2.8cm and length of two diameters was mounted flush in the center of a flat plate. The anemometer was positioned in the center of the exit hole and spectral data were taken at various suction rates. For this case the laminar separation bubble transitioned at $R_d \approx 2000$. The data in Figure 11 shows a well defined spectral peak at a Strouhal frequency fd/u=0.81. At larger R_d a wider spectrum of fluctuations occurs as breakdown of the separation bubble encompasses a wider physical dimension of the core flow. Since these data were taken in an environment with no turbulence at the entrance flow it is recommended that for LFC applications $R_d \leq 1500$.

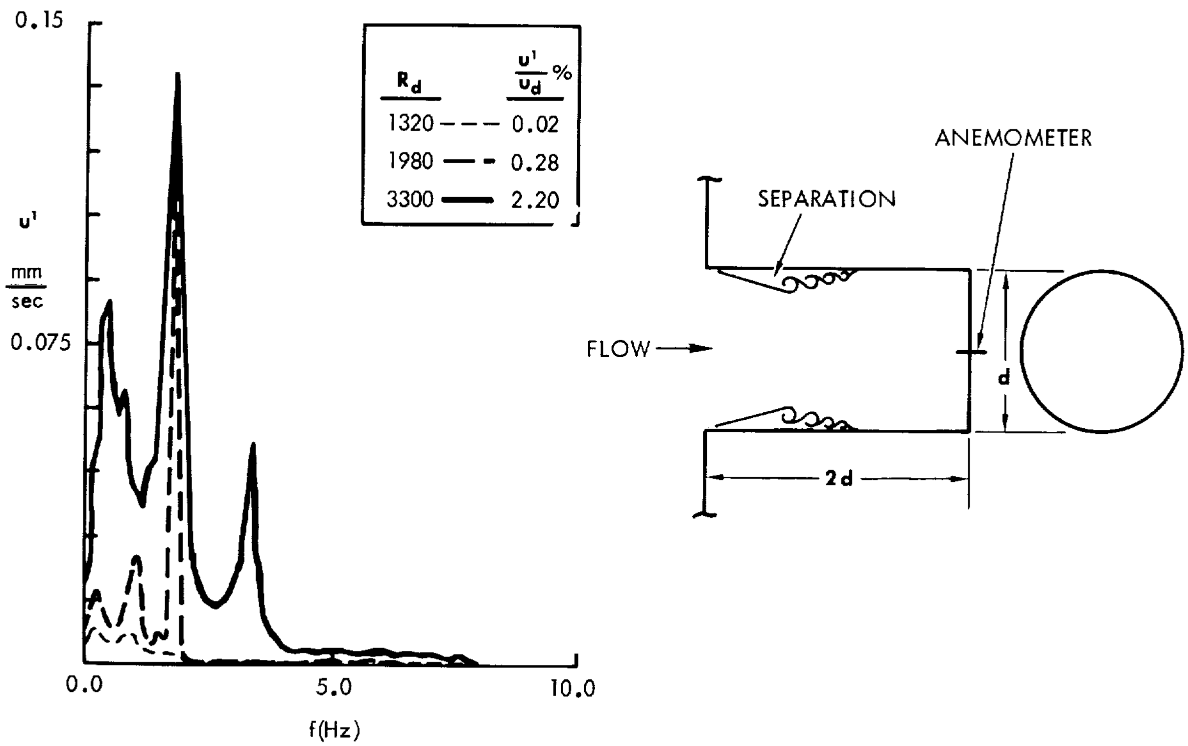


Figure 11

SLOT BLOCKAGE INSTABILITY

Ref. 10 has shown that a three-dimensional boundary-layer instability from a single row of suction holes will cause premature transition above a given suction rate. Blockage in the slot is analogous to the suction hole instability in that the mean boundary layer develops a strong spanwise gradient of vorticity adjacent to the obstruction in the slot. The three-dimensional instability growth rate will be dependent on the slot blockage width w_b and the value $R_k = U_k y_k/\upsilon$ which can be expressed in terms of the slot Reynolds number by the relationship $R_k=2.0R_s$. For the blockage study, a thin rectangular shim was placed flush across the slot width of dimensions $w_b/w_s=1.3$ with an approaching boundary-layer displacement thickness of $\delta^* = 1.5\, w_s$ and with a free stream $R_{\delta^*}=1300$.

Flow visualization confirmed that the boundary-layer vorticity coalesced behind the blocked region and was convected downstream with a discrete frequency when the slot $R_s \geq 200$. To explore this instability further the hot film probe was positioned downstream of the blocked region at $x/\delta^*=20$ at a vertical displacement of $y/\delta^* =1.0$. The suction rate was varied and the velocity fluctuations were recorded and are shown in Figure 12.

The spectral results show a large fundamental frequency with higher harmonics which demonstrate the pulse like nature of the instability for $R_s \geq 200$. For $R_s \geq 300$ the amplitude of the instability wave is sufficient for imminent transition downstream. The fundamental disturbance has a well defined Strouhal frequency of $fy_k/U_\infty=0.036$. In most cases this frequency is outside the Tollmien-Schlichting neutral stability curve and is therefore highly damped. However, at a slot $R_s=110$ the velocity perturbations are significant and may interact with the Tollmien-Schlichting instability. The spectral data show that for $R_s \leq 75$ the slot blockage instability has a negligible growth rate.

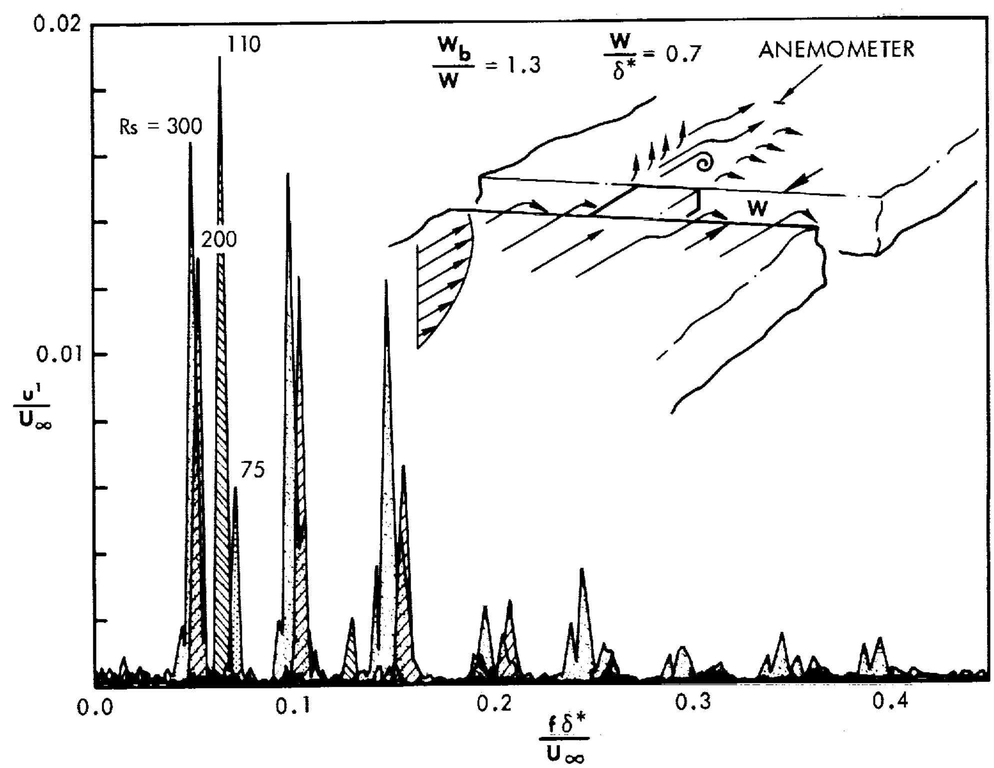


Figure 12

CONCLUSIONS

Detailed mean velocity and disturbance amplitude measurements were conducted in a Blasius boundary-layer flow with wall suction applied at three downstream locations. The main emphasis of this study was a direct comparison of the growth rate of the instability wave with discrete spanwise slots versus wide porous strips. The results demonstrate that the local effects of suction through slots or very narrow porous strips have a greater beneficial effect on the stablity of the boundary-layer flow relative to the suction influence of a wide porous strip.

Codes which use continuous suction for the growth rates of the instability waves to determine the suction quantities for a multiple series of slots will be quite conservative in the estimation of the suction quantity. To accurately determine the mean boundary-layer changes from a narrow suction strip the "sink" effect of the local suction must be accounted for in the neighborhood of the slot. This has been demonstrated in the Navier-Stokes analysis of Ref. 11.

The second part of the paper concerned an experimental study to provide guidelines for suction-chamber design and flow rates to minimize internal oscillations which propagate into the boundary-layer flow. Based on this study, the following observations are summarized:

1. The flow inside the slot has a characteristic inflectional profile due to the presence of a separation bubble, which reattaches within four slot widths. The experimental data show that the resulting shear-layer transitions at $R_s \geq 450$.

2. Oscillations from the suction chamber below the slot exit are caused from the two-dimensional jet interactions at the boundaries of the suction chamber. The velocity perturbations at the slot entrance can be minimized by a suction chamber of depth=$17w_s$ and width=$40w_s$.

3. The flow into the metering hole has a separated region which reattaches within one diameter. The perturbations of the entrance velocity becomes significant for $R_d \geq 2000$. For LFC applications it is recommended that $R_d \leq 1500$.

4. Localized slot blockage from any external debris in the environment causes a mean spanwise gradient of vorticity in the boundary layer downstream of the blocked region. The local three-dimensional boundary-layer instability which results for $w_b/\delta^* = 1.0$ has large amplitude growths for $R_s \geq 110$ with imminent transition at $R_s \geq 300$. The blockage instability has negligible growth rates for $R_s \leq 75$. Therefore, the suction Reynolds number $R_s \leq 75$ represents the upper limit to desensitize the three-dimensional instability for intermittent blockage of the slot during flight.

ACKNOWLEDGMENT

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LIST OF SYMBOLS

a	laminar separation bubble length scale inside slot
C_p	defined as $(P_o - P_\infty)/1/2\rho\, U_\infty^2$
d	diameter of metering hole
f	frequency
F	dimensionless stability parameter $2\pi f\upsilon/U_\infty^2$
m	suction parameter $v\, w/U\delta^*$
p	pitch of metering holes
P_∞	free steam static pressure
P_o	surface static pressure
R	unit Reynolds number U_∞/υ
R_k	defined as $U_k y_k/\upsilon$
R_x	Reynolds number $U_\infty x/\upsilon$
R_s	slot Reynolds number $v_s w_s/\upsilon$
R_d	hole Reynolds number vd/υ
R_{δ^*}	displacement thickness Reynolds number $U_\infty\delta^*/\upsilon$
S	Strouhal frequency
U	mean velocity in boundary layer
U_∞	free stream velocity
u'	velocity fluctuation
$\bar{u}$	RMS of velocity fluctuation
U_k	streamline velocity upstream of suction influence
v	average suction velocity at surface
v'	velocity fluctuation
w	width dimension of wall suction
x	streamwise coordinate
y	normal coordinate to surface
y_k	streamline coordinate upstream of suction influence
α	dimensionless velocity gradient parameter $\delta U/\delta y\ (w_s/v_s)$
δ^*	displacement thickness
η	$y(U_\infty/\upsilon x)^{1/2}$
θ	momentum thickness
υ	kinematic viscosity
ρ	density
τ	shear stress

SUBSCRIPTS

b	blockage
d	metering hole
k	suction streamline parameter in the boundary layer
o	reference value
s	slot
∞	free stream

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