Effects of Suction on Shock/Boundary-Layer Interaction and Shock-Induced Separation

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An experimental investigation of the effects of local boundary-layer suction on shock/boundary-layer interaction and shock-induced separation has been conducted in the DFVLR 1 m×1 m transonic wind tunnel utilizing an advanced transonic airfoil. Three different methods of suction were applied in the shock region. Their effectiveness in comparison to the basic closed-surface airfoil will be evaluated from surface pressure distribution, wake, and boundary-layer measurements. It will be shown that local boundary-layer suction in the shock region delays the development of shock-induced separation and considerably improves the overall aerodynamic characteristics. Moreover, two of the configurations investigated, viz., a double slot and a perforated strip with a cavity underneath showed, even *without suction*, a most favorable "passive" effect on shock/boundary-layer interaction and the overall flow development, thus offering a very promising means for extending the range of applicability of transonic airfoils.

Nomenclature

b	= span
b_s	= span of suction region
c	= chord length
c_D	= drag coefficient
c_L	= lift coefficient
c_p	= pressure coefficient
c_p^*	= pressure coefficient at sonic condition
$C_Q = \dot{m}/(\rho_\infty U_\infty b_s c)$	= suction coefficient
D	= drag
L	= lift
$\dot{m}$	= mass flow rate
M	= Mach number
Re	= Reynolds number (based on chord)
t	= airfoil thickness
U	= flow velocity
x	= chordwise distance from leading edge
z	= distance normal to model surface

Subscripts

B.o.	= buffet onset
e	= edge of boundary layer
s	= shock
∞	= freestream condition

I. Introduction

MAJOR advances have been achieved in aircraft development by the use of transonic airfoils which, at the design condition, have an extended region of supersonic flow on the upper surface, terminated by a nearly isentropic recompression, thus minimizing wave drag. Deviations from the design conditions, e.g., higher Mach number or incidence, result in the occurrence of a compression shock and a corresponding drag rise due in part to additional wave drag. Depending on shock strength, the boundary layer in the shock region is drastically thickened (Fig. 1), which may lead to a stationary or rapidly growing shock-induced separation bubble or trailing-edge separation, altering the whole flowfield over the rear part of the airfoil. Pearcey[1] and, most recently, Stanewsky[2] have given a detailed description of the complex interaction between the shock and the downstream flow development on transonic airfoils.

Due to the shock appearing in the flowfield and to shock-induced separation, wave and pressure drag are increased, leading with increasing freestream Mach number at constant lift at one point to a rapid rise in total drag whose onset defines the "drag-rise boundary." Ultimately, with increasing Mach number or incidence, the onset of shock oscillations, caused by severe flow separation, marks the "buffet boundary." Since at "off-design" conditions, the separation behavior of an airfoil is mainly affected by the shock, it is likely that means to control separation will be most effective if applied in the shock region, where the boundary layer is still relatively thin.

The objective of controlling shock/boundary-layer interaction is to extend the limiting boundaries. This may be accomplished by active means, as tangentially blowing[3] and boundary-layer suction,[4,5] or by passive means,[6-8] e.g., by placing in the shock region a permeable surface with a cavity beneath. Here the large pressure difference over the shock will lead to a combined suction and bleed effect downstream and ahead of the shock, respectively, which may strongly affect the boundary-layer development and shock/boundary-layer interaction.

The objective of the present experimental investigation was to study the effects of 1) different active suction methods and 2) the passive effects of a perforated strip and a double slot with a cavity underneath, positioned in the shock region, on the flow over a supercritical airfoil at off-design conditions.

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II. Experimental Details

The experimental investigation was conducted in the DFVLR 1 m × 1 m transonic wind tunnel, which is a closed-circuit continuous tunnel with 6%-open perforated walls. The model used was the two-dimensional supercritical airfoil VFW-VA-2. Figure 2 shows the general arrangement of the model in the tunnel. The model with a 200-mm chord length and a relative thickness of $t/c = 0.13$ spanned the entire tunnel width and was fixed at both ends to rotatable end plates embedded in the tunnel side walls, and employed to change the angle of attack. In the symmetry plane the pressure distribution was measured at 32 positions on the upper surface and at 22 on the lower surface; the lift was obtained by integrating the pressure distribution. Two-dimensionality of the flow on the upper surface was checked by two additional rows of pressure taps, each 200 mm off the center section. The drag forces were evaluated from wake-rate traverses two chord lengths downstream of the model. In addition, boundary-layer measurements with a combined pitot-static-directional probe were made in a plane 50 mm off the symmetry plane. The onset of buffeting was determined by schlieren observations on a video monitor and by observing the rms value of the wing root bending moment.

The basic model could be equipped with exchangeable inserts providing measurements with the surface clean, and with a single slot, a double slot, and a perforated strip. Details of the different configurations are shown in Fig. 3; a close-up photograph of the model with the double-slot insert is shown in Fig. 4. In cases with suction, the mass flow rate was measured in the suction line and set for a constant suction coefficient of $C_Q = 6 \times 10^{-4}$ by a control valve. The slots and perforation were placed at a position where the shock location at an off-design Mach number of $M_\infty = 0.78$ was expected; however, the Mach numbers covered during the experiments ranged in some cases from $M_\infty = 0.60$ to 0.86. The Reynolds number, based on chord length, was held approximately constant at $Re_\infty = 2.5 \times 10^6$ for all Mach numbers tested. In order to simulate more realistic flow conditions, the boundary layer was tripped artificially at 30% chord on the upper, and at 25% on the lower, surface.

III. Active Shock/Boundary-Layer Interaction Control by Suction

Global Effects

The effects of local boundary-layer suction in the vicinity of the shock on the aerodynamic performance of the supercritical airfoil VFW-VA-2 will first be demonstrated by the variation of force coefficients of the different model configurations before analyzing the flow about the airfoil in more detail. For the range of Mach numbers from $M_\infty = 0.74$ to 0.84 Fig. 5 shows the lift coefficients vs angle of attack for the three configurations with suction applied and for the basic closed-surface model. In comparison with the results for the latter, pronounced differences in lift can be observed for all suction variants, but marked deviations also occur between the various suction arrangements. For low angles of incidence these differences are small but grow appreciably at maximum lift conditions. The single-slot suction model which was tested only at $M_\infty = 0.78$ proves to be the most effective. Maximum lift, and accordingly the lift coefficient for the onset of buffet, is increased considerably. Similarly positive effects are gained over the whole Mach-number range tested with double-slot suction. It is remarkable that for the latter, except at $M_\infty = 0.78$ and 0.80, no distinct maximum appears in the lift curves. Suction through a perforated strip is not as effective at the lower Mach numbers, but at higher Mach numbers the lift is increased as well.

The drag too is most favorably affected by suction, as the comparison of drag coefficients for the basic closed-surface model and the suction models reveals (Fig. 6). Single-slot suction at $M_\infty = 0.78$ reduces the drag considerably for angles

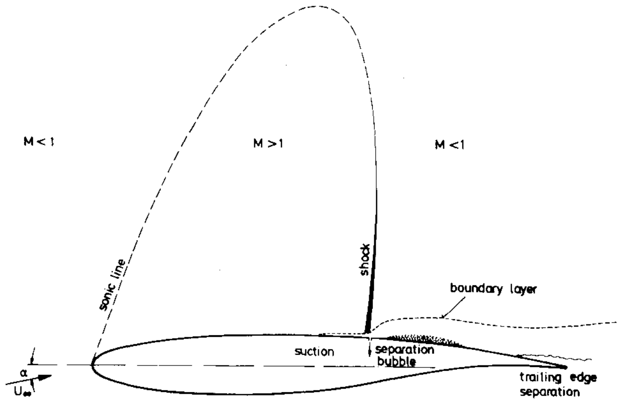

Fig. 1 Model of transonic shock/boundary-layer interaction.

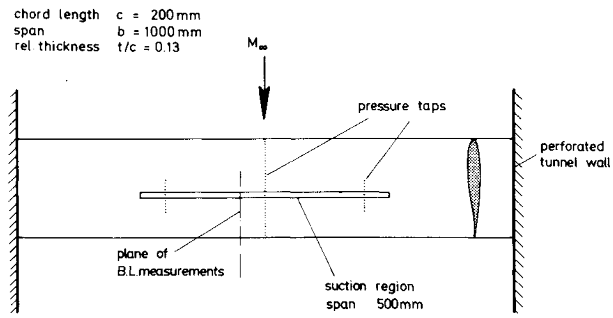

Fig. 2 Model arrangement (top view).

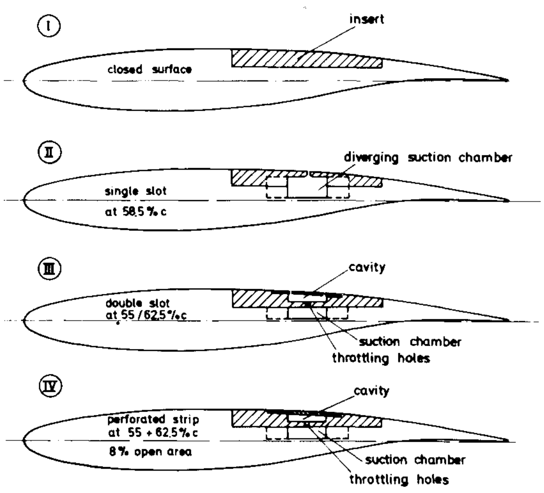

Fig. 3 Model configurations.

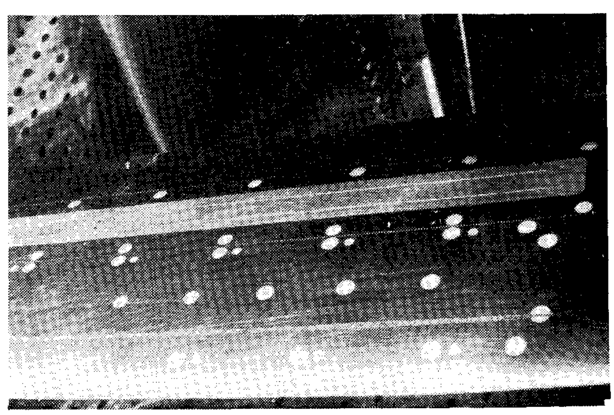

Fig. 4 Photograph of double-slot model.

of incidence $\alpha > 3.5$ deg. Double-slot suction leads to drag reductions even at low incidences. Here the differences in drag first decrease with increasing angle of attack, but at higher α (depending on Mach number) the drag is reduced drastically. For the model with suction through a perforated strip, drag coefficients were only obtained at a few angles of attack and two Mach numbers. They indicate drag reductions of the same order as double-slot suction.

Local Effects

The preceding figures have shown that the overall aerodynamic characteristics of the airfoil were altered by means of several boundary-layer suction methods. The largest improvements over the closed-surface model results were gained at higher incidences. Boundary-layer measurements were therefore made on the three suction models without and with suction at the angles of $\alpha = 4$ and 5 deg at a constant Mach number of $M_\infty = 0.78$.

Some remarks have to be made concerning problems associated with boundary-layer probe measurements on models of moderate size in transonic flow. In regions of attached flow, especially upstream of the shock, the boundary-layer thickness is very small, so that the dimensions of the probe employed (for the present measurements a 0.15-mm high flattened pitot tube) are of the same order as the boundary-layer displacement thickness. Especially at critical flow conditions, the probe-induced disturbance may be too large, leading to incorrect results. Moreover a pitot probe is not able to detect separation clearly or to measure velocities within a separation bubble correctly.

The effect of single-slot suction on the boundary-layer profiles in the shock region at $\alpha = 4$ deg is shown in the upper part of Fig. 7, the lower part depicting the boundary-layer displacement thicknesses from 45% chord to the trailing edge and the pressure distributions of the upper surface. The boundary-layer and displacement thickness is considerably reduced by single-slot suction, affecting the whole downstream flow development. Due to the effect of suction on the interaction between shock and boundary layer, characteristic parameters of the shock itself, i.e. location and strength, are affected. The pressure distribution without suction shows the shock location upstream of the suction slot. As shown by Pearcey[1] and Stanewsky,[2] the occurrence and the onset of rapid growth of a shock-induced separation bubble is indicated in the pressure distribution if the local pressure coefficient immediately behind the shock becomes smaller than the critical pressure coefficient c_p^*. The onset of trailing-edge separation is indicated by a rapidly decreasing trailing-edge pressure. In the present case, without suction a local separation bubble, about to expand rapidly, exists downstream of the shock, but at the trailing edge the flow is still attached. Shock-induced separation is delayed, or at least the extent of the separation bubble is reduced, by suction. The shock is located further downstream at the slot position. Up to this position the flow is further accelerated, increasing the shock strength. Higher shock strength and thinner velocity profiles produce additional wave and friction drag, which are, however, obviously overcompensated for by the pressure drag reduction due to reduced separation and displacement effects (see also Fig. 6).

At higher incidence, $\alpha = 5$ deg, the buffet boundary has already been reached for the single-slot model without suction (Fig. 8). The pressure distribution shows the shock far upstream and a separated region up to the trailing edge, indicated by the negative trailing-edge pressure. With suction applied, nearly the whole flowfield now is accelerated to the extremely high-preshock Mach number of $M = 1.44$ at the suction slot, which normally will lead to total separation downstream of the shock. In this case, however, the trailing-edge flow is still attached and only a local separation bubble may be induced. The large positive effect on the pressure

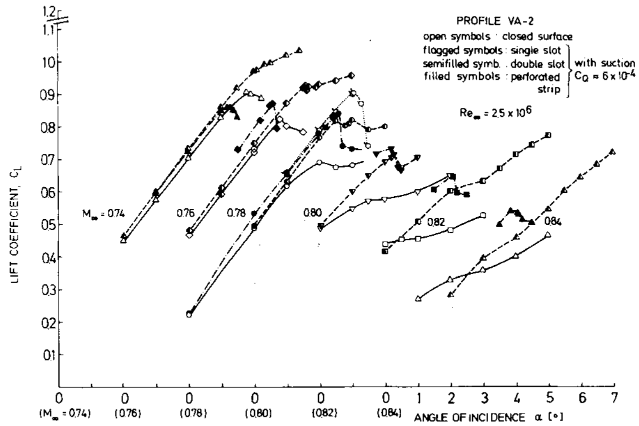

Fig. 5 Influence of suction on lift coefficients.

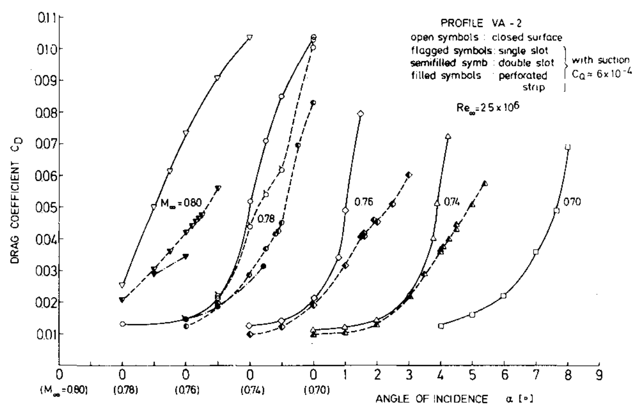

Fig. 6 Influence of suction on drag coefficients.

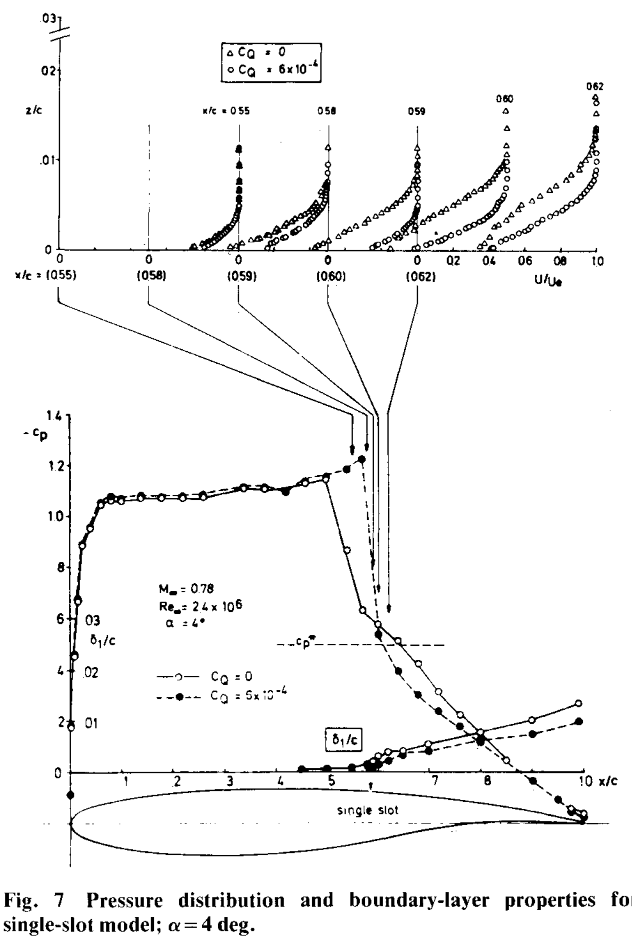

Fig. 7 Pressure distribution and boundary-layer properties for single-slot model; $\alpha = 4$ deg.

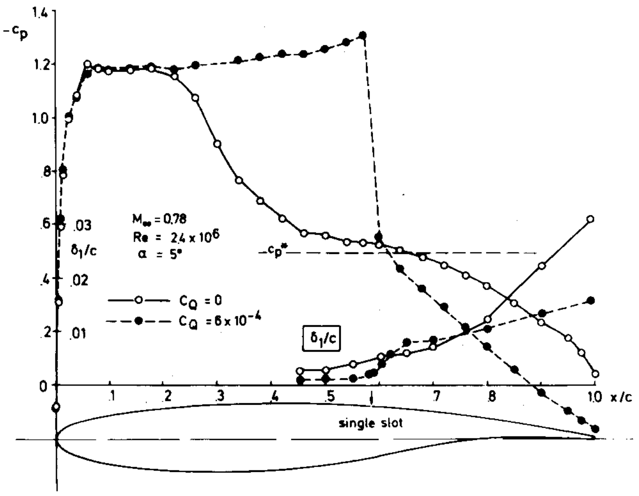

Fig. 8 Pressure distributions and displacement thicknesses for single-slot model; $\alpha = 5$ deg.

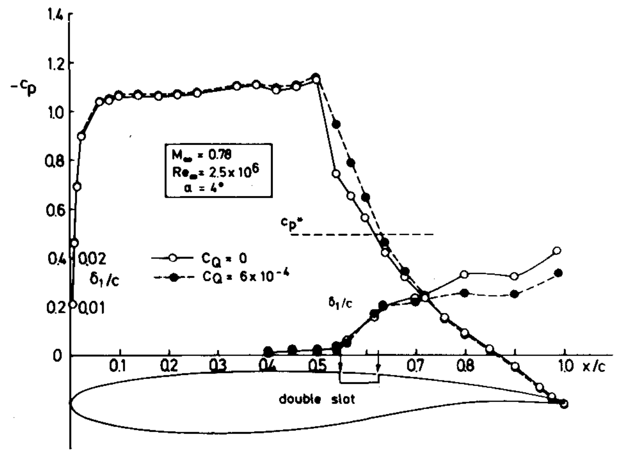

Fig. 9 Pressure distributions and displacement thicknesses for double-slot model; $\alpha = 5$ deg.

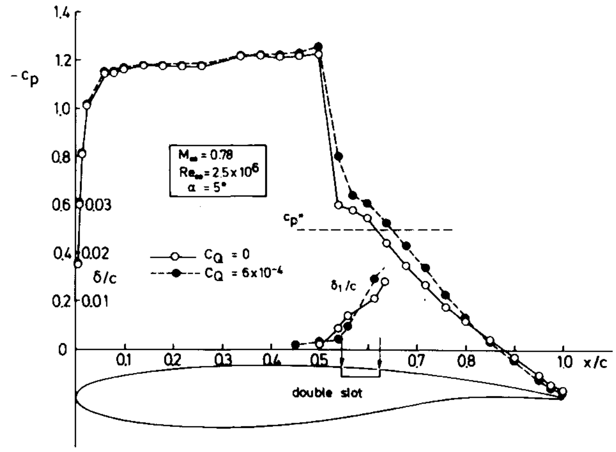

Fig. 10 Pressure distribution and displacement thicknesses for double-slot model; $\alpha = 5$ deg.

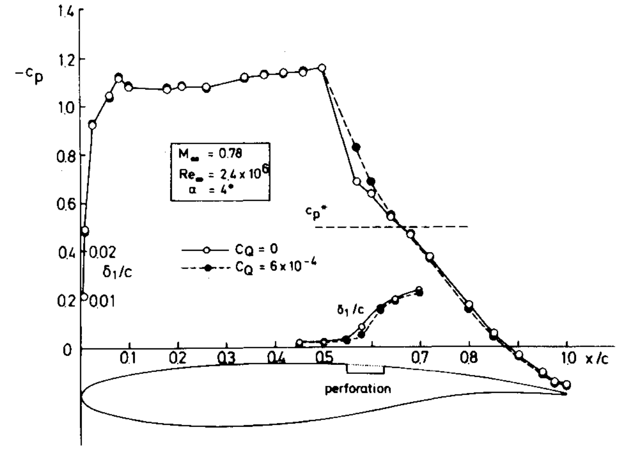

Fig. 11 Pressure distribution and displacement thicknesses for perforated-strip model; $\alpha = 4$ deg.

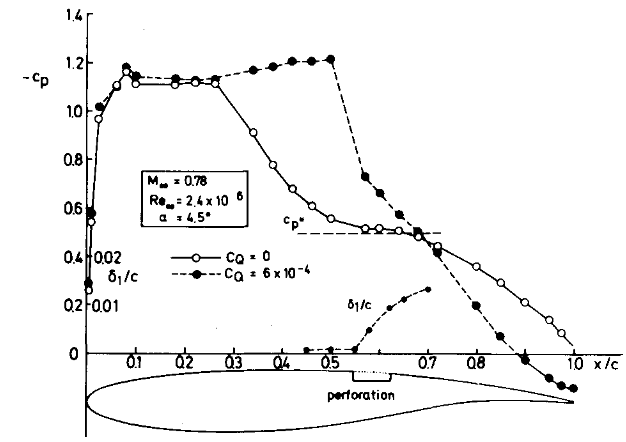

Fig. 12 Pressure distribution and displacement thickness for perforated-strip model; $\alpha = 4.5$ deg.

distribution causes corresponding changes in lift, and the reduced displacement effects result in a net drag reduction.

The pressure distributions of the double-slot configuration at $\alpha = 4$ deg (Fig. 9), as well as at $\alpha = 5$ deg (Fig. 10), show only little effect of suction. However, even without suction at $\alpha = 5$ deg, the shock is located immediately upstream of the forward slot and the pressure distribution does not indicate any trailing-edge separation. A comparison of the no-suction pressure distributions of the double-slot (Fig. 10) and the single-slot model (Fig. 8) reveals that the double slot with a common cavity, but without suction, strongly affects the flow development on the airfoil. Due to the steep pressure gradient at the slot positions, some of the boundary-layer flow is drawn into the cavity through the rear and bled from the front slot. The blowing effect at the front slot is likely to induce a separation bubble which in turn is influenced by the suction effect of the rear slot. Active suction seems to reduce the blowing at the front and to increase the suction at the rear slot, however, with nearly the same net effect on the overall flow development. Too few and insufficient measurements have been made so far to give a complete description of flow details in the suction region, including the interaction of the secondary flow through slots and cavity with the shock and the outer flow and downstream boundary-layer development. It should be noted that the investigation will be continued utilizing a larger model.

In contrast to the slot suction models, the model with a perforated strip provided area suction to be applied in the shock region. The pressure distributions and results of boundary-layer measurements at $M_\infty = 0.78$ and $\alpha = 4$ deg without and with suction are shown in Fig. 11. In both cases the shock is located upstream of the forward edge of the perforation, and the overall pressure distribution is only slightly affected by suction. The similarity in the flow development between active suction on and off is presumably again due to the "passive" suction and bleed effect discussed in the previous chapter. At higher incidence, $\alpha = 4.5$ deg (Fig. 12), the shock location is without suction, contrary to the double-slot system, far upstream and the separated region has extended to the trailing edge. By suction, separation is obviously reduced to a local separation bubble and the shock is shifted rearward, extending the supersonic flow region. These effects will increase the lift, reduce the drag, and the onset of buffeting will be shifted to higher incidence or higher lift.

The variation of the lift coefficients at highly off-design conditions (cf. Fig. 5) due to boundary-layer suction are mainly caused by the variation of the shock location. For a constant Mach number, $M_\infty = 0.78$, the shock locations vs angle of incidence for the basic closed-surface model and the three suction configurations are shown in Fig. 13. The position of the single slot, double slot, and perforation, respectively, is marked on the ordinate by arrows and the shaded region. On the basic closed-surface model, the shock commences to move upstream with increasing incidence for $\alpha > 3$ deg, reflecting the onset of separation effects. It is seen that with suction the upstream movement of the shock is generally delayed. Single-slot suction holds the shock in a position immediately upstream of the suction slot up to $\alpha = 5$ deg, while with double-slot suction the shock is located in front of the rear slot, starting to shift upstream at $\alpha > 4.5$ deg but not as rapidly as in the case of the single-slot or the perforated-strip configuration.

IV. Passive Shock/Boundary-Layer Interaction Control

It was shown in Figs. 9-11 that for the double-slot and perforated-strip configurations there is only a small effect of suction on the overall airfoil flow development. These configurations yield, however, as indicated in Figs. 5 and 6, an appreciable increase in lift and a considerable drag reduction when suction is applied. This suggests that there must already be a strong "passive" effect on shock/boundary-layer interaction as a result of the mere presence of the double slot or the performation with the cavity located underneath.

In Fig. 14, lift coefficients of the double-slot model and perforation model without suction are compared with the corresponding closed-surface model results. At $M_\infty = 0.74$ the maximum lift is lower for the perforated model, but at the higher Mach numbers the maximum lift is considerably increased. For the double-slot configuration the passive effect is favorable at all Mach numbers with lift increasing steadily with increasing angle of incidence showing no distinct lift maxima. The most striking results of the double-slot model investigation were that in the Mach-number range tested, contrary to the other configurations, no shock oscillations were detected in schlieren observations and that at Mach numbers between $M_\infty = 0.70$ and 0.80 only weak buffeting was indicated by the rms value of the airfoil root bending moment. Buffeting ceased completely at $M_\infty > 0.82$, even so, the flow was fully separated downstream of the shock to the trailing edge. It seems that with the double-slot configuration the normally very strong coupling between shock and trailing-edge flow conditions is interrupted or largely suppressed by the slots with the cavity beneath, which probably acts as some kind of damping mechanism. The present measurements are unable to reveal more details of the nature of this effect, and further investigations will be necessary.

The gain in lift is again due largely to the strong effect of the double-slot and the perforated-strip configuration,

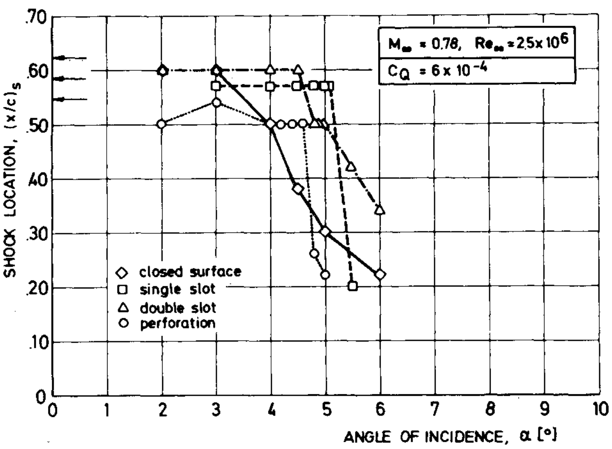

Fig. 13 Influence of suction on shock location.

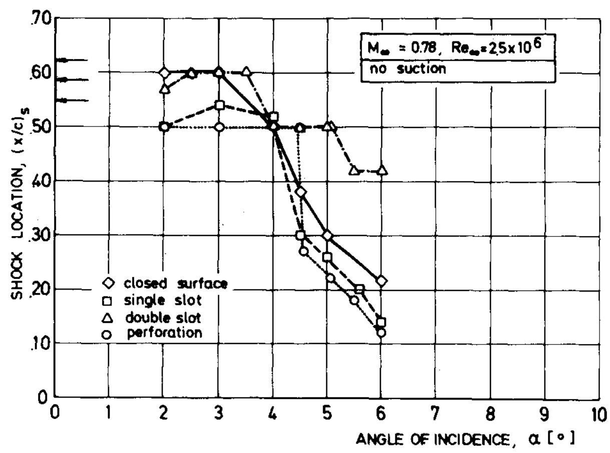

Fig. 15 Shock location, suction off.

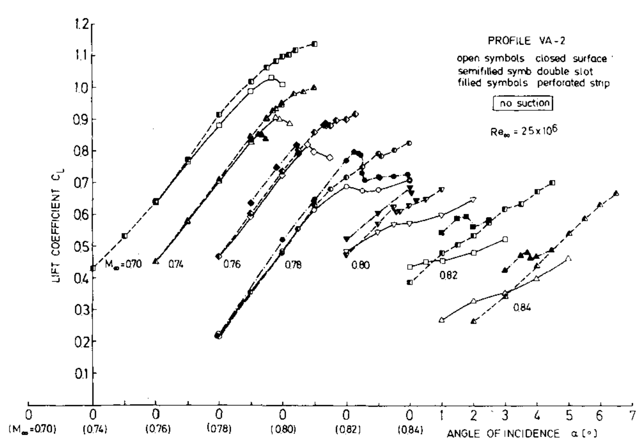

Fig. 14 Lift coefficients, suction off.

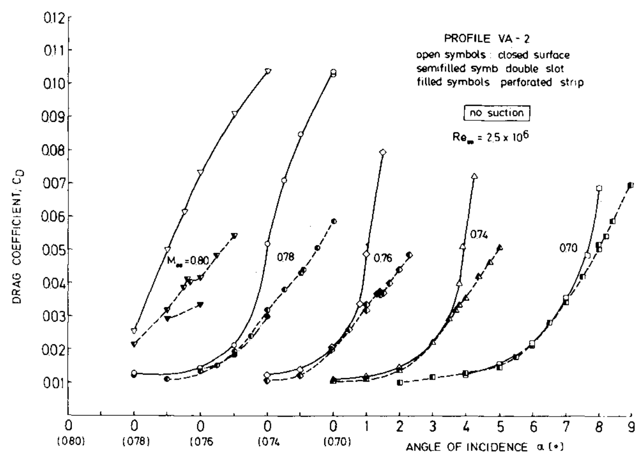

Fig. 16 Drag coefficients, suction off.

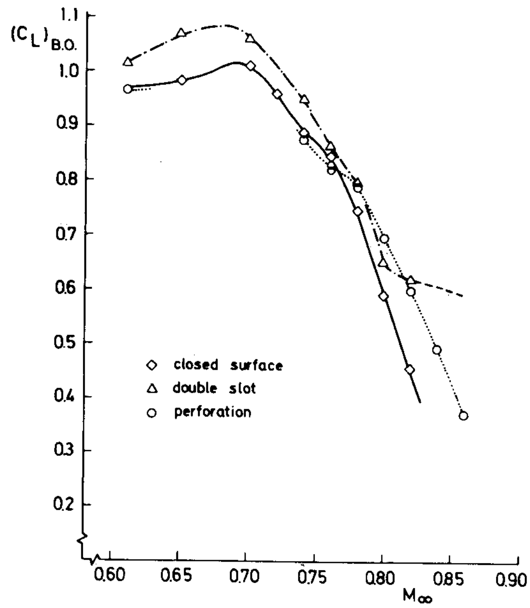

Fig. 17 Buffet boundaries, suction off.

respectively, on the shock location (Fig. 15). The shock behavior is similar to the one described for these configurations with "active" suction applied.

Reducing the drag is, of course, one of the main objectives in transonic airfoil design. In addition to a proper shaping of the profile, the passive effect of the double-slot and perforated-strip arrangements offer a potential for further improvements. This is demonstrated in Fig. 16, where the drag coefficients for these configurations without suction are compared with the ones for the basic closed-surface model. Even at low incidence, the drag is slightly reduced, the greatest reductions, however, are obtained in the regime of very strong shock/boundary-layer interaction.

In experiments by Bahi et al.[6] a porous surface of 30% chord with a cavity underneath, positioned at the shock location, on a supercritical airfoil at zero incidence, was used to reduce the wave drag by reducing the shock strength. Preliminary investigations for suppressing shocks on a transonic airfoil by using a perforation with cavity from close to the leading edge to close to the trailing edge were made by Savu et al.[7] In the present investigation the perforated strip and cavity covered only 7.5% chord, and no considerable reduction in shock strength was observed. It is therefore believed that the large drag reductions obtained here are mainly due to the passive effect of double slot and perforation on the separation behavior of the airfoil, although some relaxation of the pressure gradient in the shock/boundary-layer interaction region is indicated in Figs. 9 and 11.

As mentioned earlier, the ultimate boundary of applicability of a transonic airfoil (at least for transport-type aircraft) is the buffet boundary. Figure 17 shows how this boundary is shifted due to the passive effect of the double-slot and the perforated-strip arrangements on shock/boundary-layer interaction and the associated overall flow development. At $M_\infty < 0.78$ the perforation exhibits no effect on buffet onset, but beyond this Mach-number buffet is delayed to considerably higher Mach numbers or lift coefficients, respectively. The double slot, on the contrary, increases the buffet boundary in the entire Mach-number range investigated. For this configuration, buffeting was only weak, and at $M_\infty > 0.82$ no buffeting could be detected at all.

V. Conclusion

The present experimental investigation has shown that by active means, i.e., local boundary-layer suction in the shock region, the overall aerodynamic performance of transonic airfoils at off-design conditions can be considerably improved. The improvements are gained by affecting the shock/boundary-layer interaction and the separation behavior downstream of the shock. The thickening of the boundary layer due to the shock is considerably reduced by suction and shock-induced separation, and the rapid growth of the separation bubble is delayed. The shock is held in its most rearward position up to higher incidences, thus increasing the lift. (Single-slot suction proved to be most effective at $M_\infty = 0.78$.) The delay in the development of separations also leads to a reduction of pressure drag, which overcompensates for the additional friction and wave drag due to fuller velocity profiles and higher shock strengths. Thus, appreciable net drag reductions are obtained.

Comparison of the results for the models with the double-slot and the perforated-strip arangements *without suction* with the corresponding reference measurements on the basic closed-surface model has indicated a favorable "passive" effect. Here the secondary flow caused by the pressure gradient over the double-slot or perforated region affects the interaction between shock and the boundary-layer flow downstream of the shock. Whereas for the lower Mach numbers the passive effect diminishes on the perforation model, its favorable effect is present on the double-slot configuration over the entire Mach-number range tested. Especially at high incidence the passive effect of the double slot on the shock/boundary-layer interaction results in large increases of lift and in considerable drag reductions.

The most striking result of the double-slot configuration, however, was that even at high angles of attack with fully separated flow between upper surface shock and trailing edge, no severe buffeting, and at $M_\infty > 0.82$ no buffeting at all, was observed. The normally very strong interaction between shock and downstream flow development is obviously suppressed by the double-slot cavity arrangement and the associated secondary flow.

The present measurements did not allow a complete assessment of the flow development associated with the passive shock/boundary-layer interaction control. Further investigations on a larger model with the use of more sophisticated measuring techniques are planned and are anticipated to give some deeper insight into this flow phenomenon.

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