Further Investigations of Transonic Shock-Wave Boundary-Layer Interaction with Passive Control

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Passive control experiments were conducted on a wall-mounted half-model, with a supercritical profile, in a small transonic tunnel. The shock Mach number M_{so} was in the range $1.2 < M_{so} < 1.34$. The momentum thickness Reynolds number R_θ at the foot of the shock was 5.7×10^3. The results indicated that a significant drag reduction in transonic flow can be obtained by passive control, which was broadly in agreement with similar experiments conducted at Rensselaer Polytechnic Institute at $R_\theta \simeq 3 \times 10^3$ and experiments conducted at Queen's University, Belfast, on a circular arc model at $R_\theta = 10 \times 10^4$.

Nomenclature

C_D = profile drag coefficient
C_p = pressure coefficient
c = model chord length
d = diameter of the holes
H = boundary-layer shape factor
h = tunnel height
h_c = cavity depth
L^* = interaction length
M = freestream Mach number
M_{so} = shock Mach number, solid model
p_o = total pressure in the wake
$p_{o\infty}$ = total pressure in the freestream
p = porosity, ratio of open area to model area
U_∞ = velocity at the edge of the boundary layer
u = local velocity in the boundary layer
t = model thickness
X_{so} = shock position, solid model
x = distance along the model chord line
y = distance normal to the model chord line
δ = boundary-layer thickness at $u = 0.995U_\infty$
δ^* = boundary-layer displacement thickness
θ = boundary-layer momentum thickness

Introduction

TRANSONIC flow over an airfoil contains supersonic regions embedded in a subsonic flow. The supersonic flow invariably terminates in a shock wave that results in wave drag. The interaction between a shock wave and boundary layer may lead to boundary-layer separation which constitutes additional drag. Unsteady pressures associated with a shock boundary-layer interaction can also induce high levels of buffeting.

Postponement of Mach number at which significant increases in drag and buffet occurs would require the control of shock boundary-layer interaction. One of the possible control techniques that appears to be promising is the passive control of shock boundary-layer interaction (PCSB) schematically illustrated in Fig. 1. The concept[1,2] consists of a porous surface and a cavity located at the foot of the shock. The natural static pressure rise across the shock sets up a recirculating airflow, the upstream effect of which would thicken the approaching boundary layer and soften the shock system reducing the wave drag. It could be conceivable that suction of the boundary layer behind the shock can also control separation.

Initial passive control experiments conducted at Rensselaer Polytechnic Institute (RPI) by Nagamatsu et al.[3] on a wall-mounted supercritical airfoil in a small transonic tunnel showed that a significant drag reduction in transonic flow can be achieved by PCSB. The pressure distribution and the wake profile measured in these experiments indicated that passive control reduces both the entropy changes across the shock wave and viscous losses within the boundary layer by softening the shock system and by suction of the boundary layer downstream of the shock wave. Experiments conducted at Queen's University of Belfast (QUB)[4–8] on a wall-mounted circular arc profile showed that the drag reduction was primarily achieved by softening of the shock system. These experiments also indicated that a porous surface consisting of holes that are inclined and facing upstream is better suited

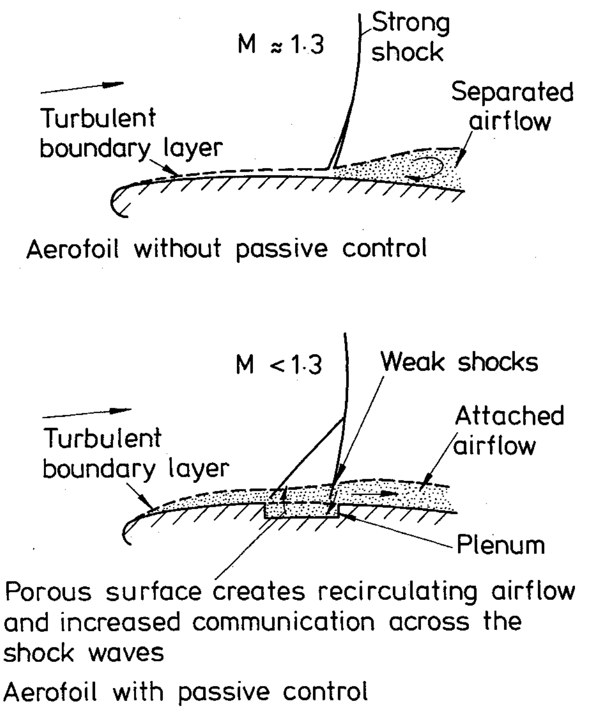

Fig. 1 Shock boundary-layer interaction with and without passive control.

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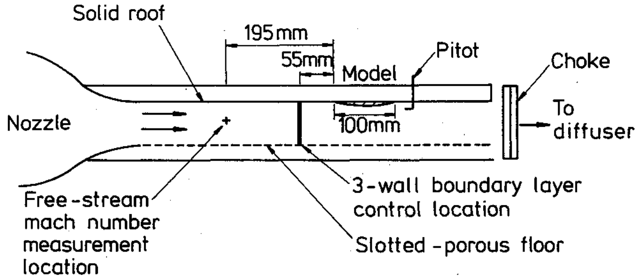

Fig. 2 Schematic diagram of the test setup.

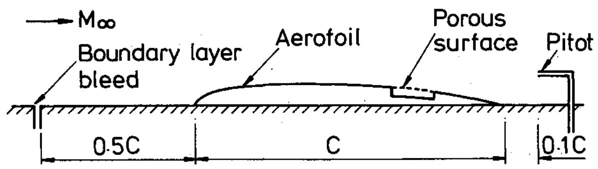

Fig. 3 Model details.

than a porous surface consisting of normal holes for drag reduction. The experiments at RPI[1-3] were conducted with a turbulent boundary layer, thin relative to the chord size of the model, in order to simulate the boundary layer at the foot of the shock nearer free-flight conditions. This, however, resulted in a low value of R_θ estimated to be about 3×10^3. At these low values of R_θ the shock-wave boundary-layer interaction was essentially influenced by viscous forces. The experiments at QUB[4-8] were also conducted with a turbulent boundary layer, but thick relative to the chord size. This resulted in a much higher value of $R_\theta = 10 \times 10^4$, which was closer than that which can be obtained on an airfoil in the freestream of larger wind tunnels. But these experiments, because of a thick boundary layer at the foot of the shock, were subjected to trailing-edge separation.

The only PCSB experiments conducted on an airfoil with circulation were those of Krogamann et al.[9] In these experiments, several types of porous surfaces were used. The experiments with a slotted porous surface showed a considerable reduction in drag and also an increase in lift. The mechanism producing the changes in lift and drag were not clear from the experiments.

This paper presents experimental investigations undertaken to obtain a further understanding of the PCSB. The model in

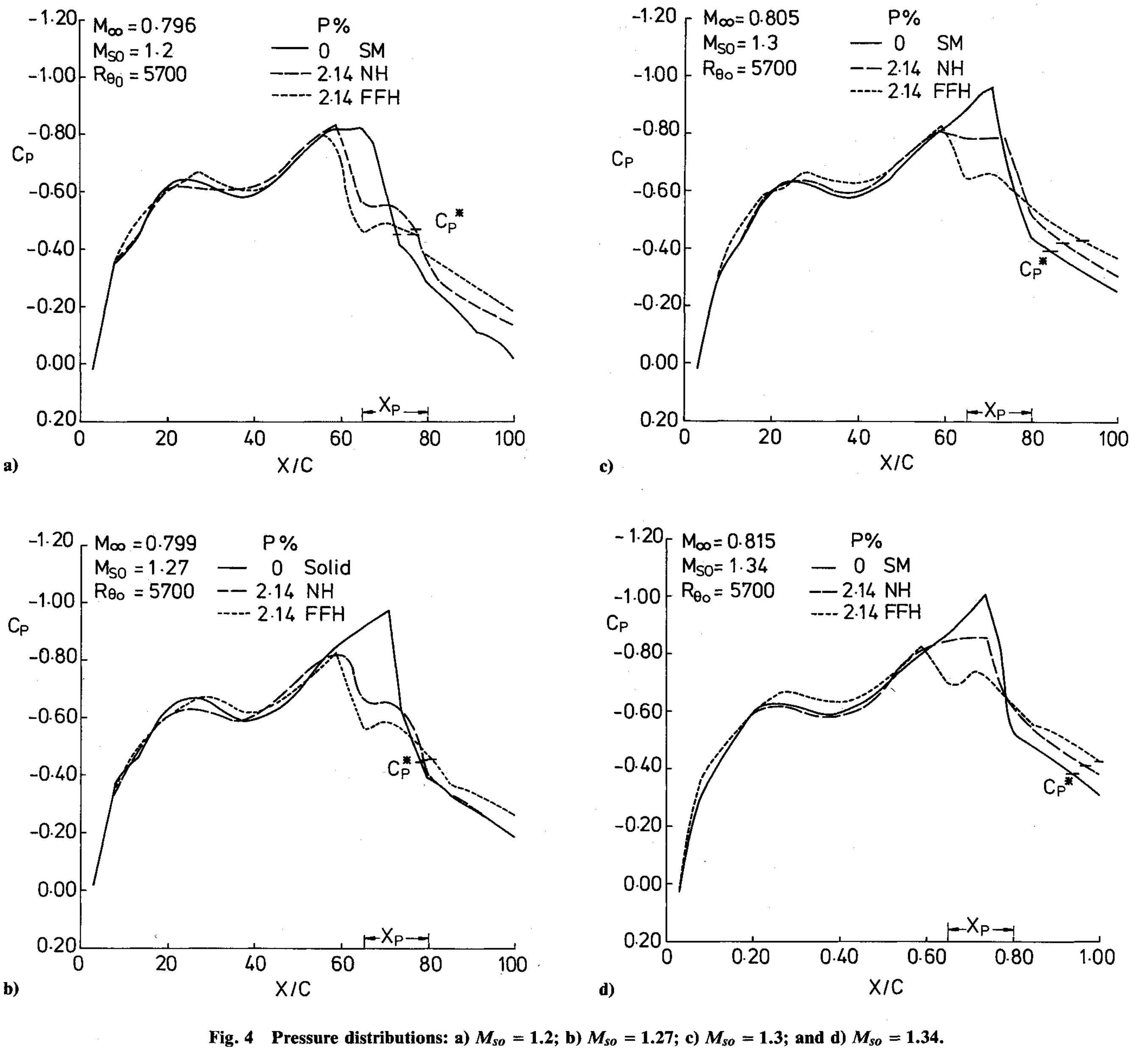

Fig. 4 Pressure distributions: a) M_{so} = 1.2; b) M_{so} = 1.27; c) M_{so} = 1.3; and d) M_{so} = 1.34.

these experiments was wall mounted and had the same profile as that investigated at RPI. A boundary-layer bleed upstream of the model was used to produce a thin boundary layer. Experiments were conducted with porous surfaces made of inclined holes and normal holes for freestream Mach numbers in the range of $1.2 < M_{so} < 1.34$. The results are compared with the other experiments.

Test Facility, Models, and Test Conditions

Experiments were conducted in a 101-mm square blowdown transonic tunnel with an atmospheric intake. The test section (Fig. 2) had closed side walls and a slotted floor with two slots covered with screens. The porosity of the floor was 9.6%.

The model was a half-model of a NACA 14% thick supercritical airfoil that had the same profile given in Ref. 1. The model chord length was 101 mm. The model blockage was $t/h = 0.07$, and the effective chord to tunnel height was $c/h = 0.5$. The generally recommended values of t/h were less than 0.015. However, these were not regarded as critical as the measurements were only of a comparative nature. Boundary-layer suction was applied both to the side walls and the tunnel roof at a distance $0.5c$ upstream of the model leading edge, which resulted in a value of $R_\theta = 5.7 \times 10^3$ and $\delta^*/c = 5 \times 10^{-3}$ at the foot of the shock. This value of R_θ is about twice the estimated value for the experiments of Refs. 1–3, but nevertheless the shock boundary-layer interaction in both cases is likely to be dominated by viscous forces. One solid model and two porous models were tested. For the porous models, the porous region consisted of 1-mm-diam holes located in the region $0.65 < x_p < 0.80$. The holes were normal to the surface for the normal-holes (NH) model and inclined at 60 deg to the normal to the chord lines and facing upstream for the forward-facing holes (FFH) model.

The ratio of diameter of the holes to the boundary-layer displacement thickness upstream of the shock was $d/\delta^* = 2$. The porosity of the models, based on the open area to total model planform areas, was $p = 2.14\%$. The cavity depth beneath the porous surface had an average depth of $h_c = 6.20$ mm resulting in a value of $h_c/\delta^* = 12.5$. All of the models had pressure orifices located at 5-m intervals up to midchord position and 2.5-mm intervals between the midchord and the trailing edge.

Shock Mach numbers of $M_{so} = 1.2$, 1.27, 1.3, and 1.34 with reference to the solid model (SM) were chosen as test conditions.

The shock position was within the range $0.6 < X_{so}/c < 0.75$.

A Scanivalve with a pressure storage box was used for the pressure measurements. Wake traverses were performed at a position $x/c = 1.1$ on the centerline of the model. A pitot tube with a front opening of 1.3 mm × 0.25 mm and a Druck PDCR 32 transducer was used for this purpose. Shadowgraph pictures were taken for the three test conditions on all three models.

The freestream Mach number was based on a sidewall pressure measurement two chords upstream of the model leading edge. The Mach number in the tunnel was controlled by a wedge located downstream of the test section (Fig. 3).

It should be emphasized that the model test did not fulfill the circulation and trailing conditions of a lifting airfoil and was subjected to blockage effects and therefore was intended only as a comparative test.

Results and Discussions

Comparison of pressure distribution on the model with and without passive control for shock Mach numbers of $M_{so} = 1.2$, 1.27, 1.3, and 1.34 shown in Figs. 4a–4d, respectively, indicate the following general features of passive-controlled shock boundary-layer interactions:

1) Passive control reduces the pressure gradients in the interaction region. The only sharp changes in the pressure distribution are near the beginning and end of the porous region. The peak negative pressure is reduced.

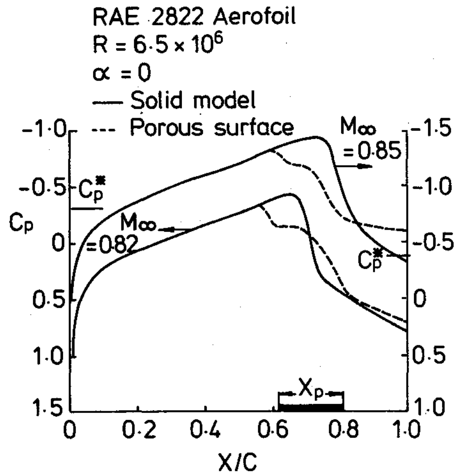

Fig. 5 Pressure distributions (theoretical) based on Ref. 10.

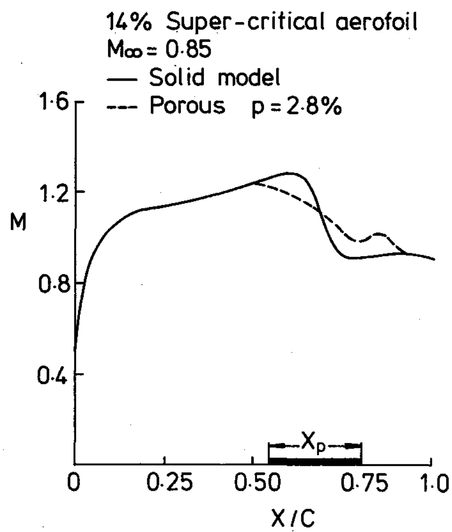

Fig. 6 Pressure distributions (experimental) from Ref. 2.

2) A single shock wave is split into two shock waves. (This was confirmed by schlieren photographs.)

3) Passive control increased the interaction length, which is the distance between the position of the peak Mach number and Mach number of unity. This would suggest increased communication in the interaction region and therefore increased upstream influence.

4) Passive control also produced a hump in the pressure distribution in the interaction region. This would indicate a change in effective geometry possibly due to a recirculating airflow in the porous region.

5) Passive control is sensitive to the type of porous surface.

These general features of PCSB are similar to those observed from experiments on the same profile at RPI[2] (Fig. 5) and theoretical predictions by Chen et al.[10] (Fig. 6). The only discrepancy appears to be the effect of passive control on trailing-edge ($x/c = 1$) pressures. Figures 4 and 6 show that the PCSB reduced the trailing-edge pressure, whereas Fig. 5 shows that PCSB had no effect on the trailing-edge pressure. This discrepancy, to some extent, could be attributed to the differences in Reynolds number and blockage effects in experiments particularly for test conditions corresponding to $M_{so} > 1.3$. Other plausible reasons are given later in the paper.

The experiments on PCSB on a lifting airfoil by Krogamann et al.[9] shows a totally different picture (Figs. 7a and 7b). The results of a porous surface consisting of double slots (Fig. 7a)

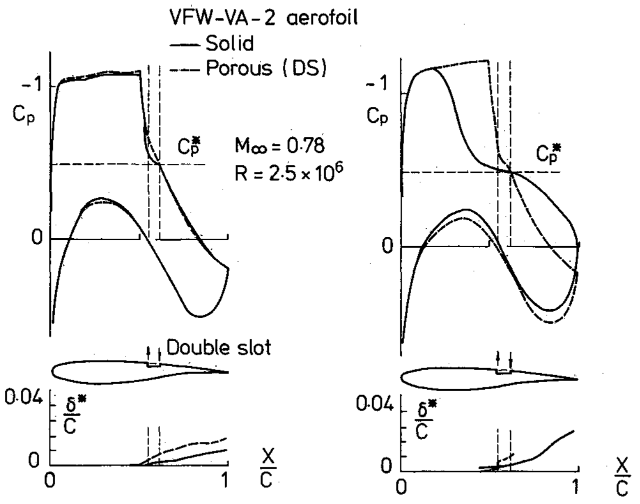

Fig. 7 Pressure distributions on an airfoil with circulation (from Ref. 9): a) passive control at the shock position; and b) passive control downstream of the original shock.

showed that no significant change in the shock strength was produced by PCSB. Significant changes in the pressure distribution were observed only when the porous surface was located downstream of the original shock position (Fig. 7b). In these experiments, PCSB either produced no change in the trailing-edge pressure (Fig. 7a) or increased the trailing-edge pressure (Fig. 7b).

The effect of passive control on shock position is shown in Figs. 8a and 8b. On a porous surface, the shock system is spread with the leading-edge shock wave oblique and anchored nearer the beginning of the porous region. The trailing-edge shock wave is nearly normal and generally within the porous region for normal holes (Fig. 8a) and near the end of the porous region for the forward-facing holes (Fig. 8b). This feature is in general agreement with earlier work on a circular arc model[4,7] and the observations by Nagamatsu et al.[1-3] (Fig. 9). The spread of the shock system on a porous surface has also been predicted theoretically.[10]

The relative losses in a shock boundary-layer interaction can be understood from a plot downstream of the interaction of stagnation pressure $p_o/p_{o\infty}$ vs distance normal to the surface y/c. Within the boundary layer and close to the surface the losses are essentially viscous losses, whereas outside the boundary layer the losses are due to entropy increases across the shock wave. An integral value given by

$$I_w = \int_0^\infty (1 - p_o/p_{o\infty})\, d(y/c)$$

is a measure of the loss of total pressure due to shock boundary-layer interaction. Comparison of the measurements of stagnation pressure profiles in the wake 10% chord downstream of the model trailing edge are shown in Figs. 10a–10c for three shock Mach numbers $M_{so} = 1.2$, 1.3, and 1.34, respectively. The boundary-layer thickness corresponds to a value of y/c typically of 0.12. The results of the porous surface made of normal holes shows that for all shock Mach numbers, passive control increases the viscous losses within the boundary layer but decreases the entropy changes across the shock wave. This result is consistent with those of earlier tests on a circular arc airfoil[4,7] and theoretical prediction by Chen et al.[10] The experiments of Nagamatsu et al.[1-3] showed that passive control can also reduce viscous losses within the boundary layer (Fig. 11). Reduction in viscous losses within the boundary layer was obtained in the present experiment

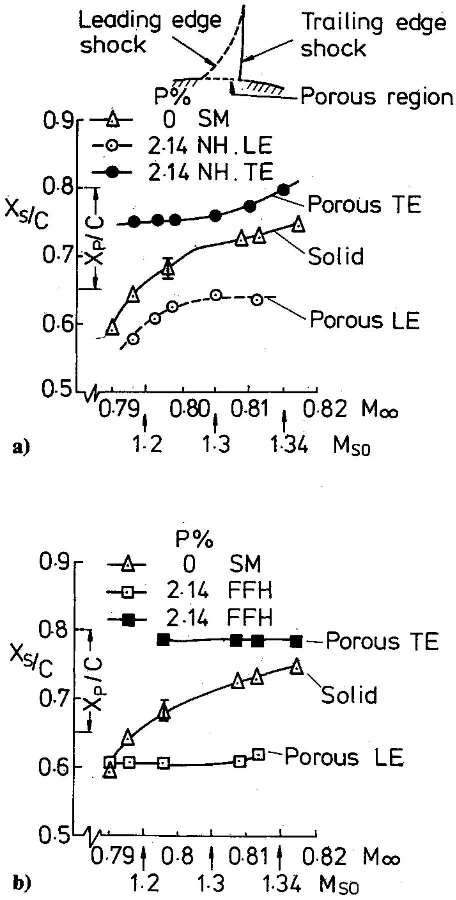

Fig. 8 Effect of passive control on shock position: a) normal holes; and b) forward-facing holes.

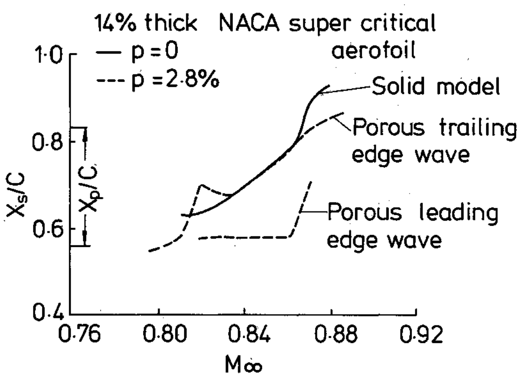

Fig. 9 Effect of passive control on shock position (from Ref. 3).

with forward-facing holes but only at relatively high shock Mach number (Fig. 10c). Similar results were obtained in earlier experiments on circular arc model.[5,8]

The variations with Mach number of boundary-layer displacement thickness δ_w^*/c, shape factor H_w, and integral value of total pressure losses I_w based on the measurements 10% chord downstream of the model trailing edge, are shown in Figs. 12a–12c, respectively.

For the solid model, δ^*/c and H_w (Figs. 12a and 12b) increase considerably at a shock Mach number $M_{so} \simeq 1.3$ showing the significant effect of shock-induced separation. For $M_{so} < 1.3$, passive control thickens the boundary layer and makes the boundary layer less full possibly due to the dominating effect of blowing-over suction in the interaction region.

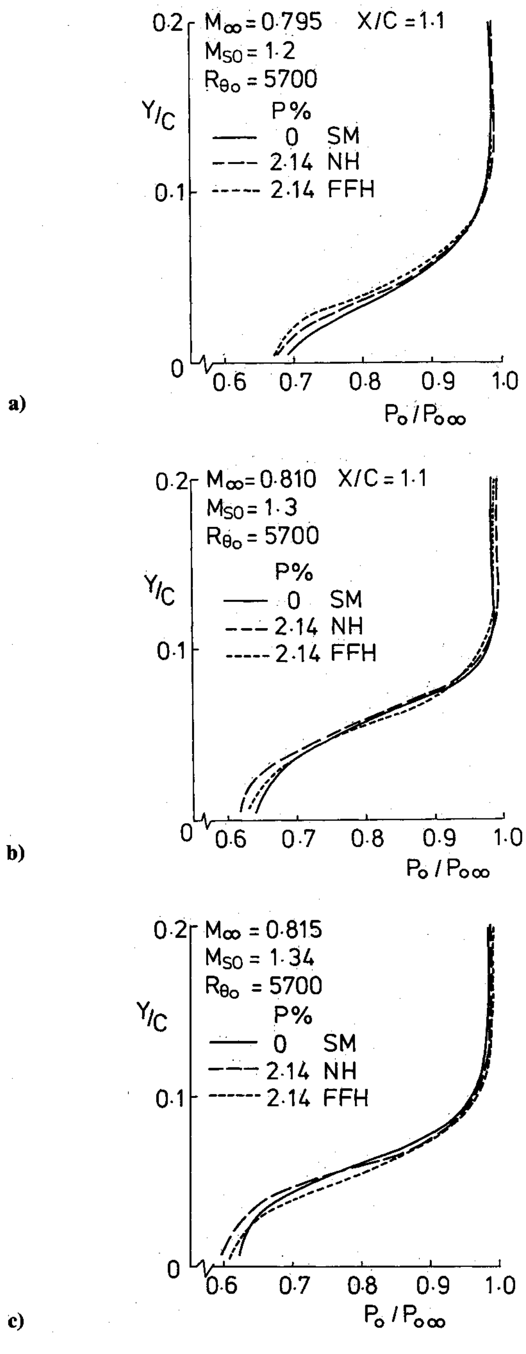

Fig. 10 Stagnation pressure profiles: a) M_{so} = 1.2; b) M_{so} = 1.3; and c) M_{so} = 1.34.

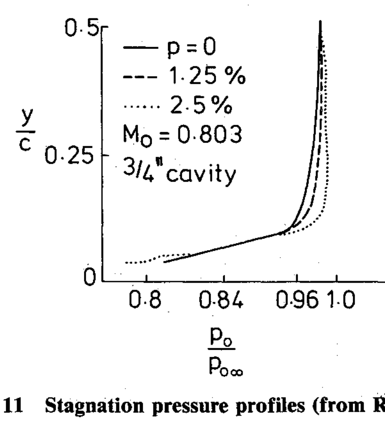

Fig. 11 Stagnation pressure profiles (from Ref. 1).

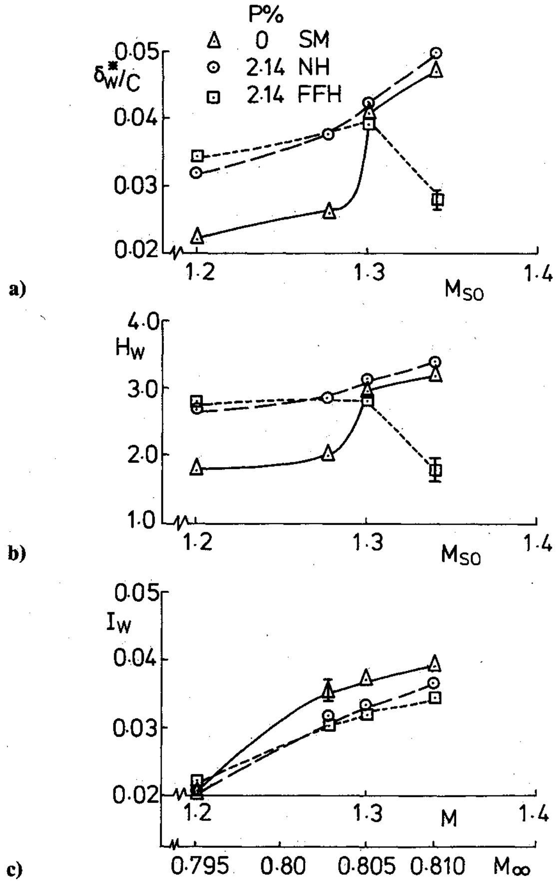

Fig. 12 Wake measurements: a) displacement thickness; b) shape factor; and c) stagnation pressure loss.

For $M_{so} > 1.3$ and with passive control with normal holes, the measured values of δ_w^*/c and H_w are only slightly higher than those corresponding to the solid model. Theoretical calculations on the RAE 2822 airfoil[10] and some boundary-layer measurements on a circular arc profile[7] also show that passive control thickens the boundary layer. Only the forward-facing-holes model at a high shock strength shows some suction effects. It could be argued that the boundary-layer development in the subsonic region downstream of the airfoil is a function of upstream boundary-layer influence. With passive control, the boundary layer approaching the shock interaction is thicker and, when subjected to a shock interaction, even with a softened shock system, takes a long distance to rehabilitate itself and is less resistant to separation. This would result in a thicker boundary layer downstream of the interaction. This argument would support the predicted[10] and measured[5,8] values of trailing-edge pressure, shown to be lower with the passive control. The thickening of the boundary layer downstream of the shock wave and therefore the decrease in the trailing-edge pressure can be reduced when considerable suction effect is present, which appears to be the case with the results of Nagamatsu et al.[1-3] and Krogamann et al.[9]

The results for the integral value of stagnation pressure loss (Fig. 12c) show that the beneficial effect of passive control in reducing the overall losses is only at $M_{so} > 1.3$ and forward-facing holes are better suited than normal holes for reducing the losses. These observations are consistent with earlier experiments on a circular arc model.[4,7]

The drag reductions $\Delta C_D = C_{DO} - C_D$ normalized with respect to C_{DO}, where C_D is the drag coefficient based on wake traverse for the porous model and C_{DO} is the corresponding

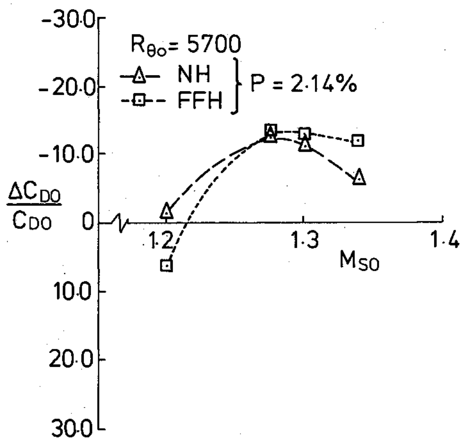

Fig. 13 Drag reduction with passive control.

drag for the solid model, are plotted against M_{so} in Fig. 13. The drag reductions with passive control are about 10% at high shock Mach numbers, which compares with reductions of 10–30% obtained in other experiments.

Conclusions

Passive control boundary-layer experiments were conducted on a wall-mounted half-model with a supercritical airfoil profile. The results of the experiments were in broad agreement with similar experiments conducted at Rensselaer Polytechnic Institute and experiments conducted at Queen's University of Belfast on a circular arc model. Some of the discrepancies observed between various experiments were attributed to wind-tunnel blockage and scale effects. It is suggested that detailed experiments in a large wind tunnel should be conducted in order to resolve these discrepancies and to understand fully the passive control shock-wave boundary-layer interaction.

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