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Multiple Slot Skin Friction Reduction

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Introduction

ATTEMPTS by fluid dynamicists to minimize skin friction drag on aerodynamic vehicles has received considerable attention in the past. Various methods have been investigated, but associated and often frustrating penalties or hardware problems have prevented the development of functional and economical systems for full scale aircraft application. In light of increased energy costs, there is a resurgence of interest in viscous skin friction drag reduction techniques.[1] In addition, techniques for reducing aircraft form drag have increased the percentage of the total aircraft drag attributable to viscous effects.

One possible technique for reducing skin friction drag is to inject relatively low momentum air through discrete tangential slots on external surfaces of an airplane (i.e., slot injection). Although numerical and experimental studies at high speeds have shown the potential of slot injection as a skin friction reduction technique,[2-5] there is little experimental skin friction data for discrete slot injection in subsonic flows. This paucity of low-speed skin friction data with slot injection prevents a realistic systems analysis of slot injection as a viable drag reduction technique. The purpose of the present study was to investigate analytically the effect of slot injection on skin friction for a representative fuselage shape (ogive-cylinder body) and to indicate the potential of slot injection as a drag reduction system in subsonic flow. The numerical technique used[6] was selected because it predicted well the experimental slot injection skin friction data obtained at supersonic and hypersonic speeds.

Description of the Investigation

The study was conducted for typical CTOL cruise flight conditions and a fuselage shape representative of current long-haul subsonic transports. The Mach number and altitude chosen were 0.82 and 11 km, respectively. The fuselage length (L) was 67.06 m with a maximum diameter of 7.32 m. the shape of the fuselage was defined by the following equations

$$r = \frac{3}{55}\left[1 - \left(\frac{11(x)-2}{2}\right)^2\right]^{1/2} \quad \text{for } 0 \leq x \leq \frac{2}{11}$$

$$r = \frac{3}{55} \qquad \text{for } \frac{2}{11} \leq x \leq 1.0$$

where r and x are the local body radius and axial distance normalized by L. The surface pressure distribution up to the first slot ($x=0.09$) was determined for the given body shape from the method of Ref. 7; from the first slot to the end of the fuselage the local pressure was assumed constant and equal to the freestream static pressure. The numerical method of Ref.

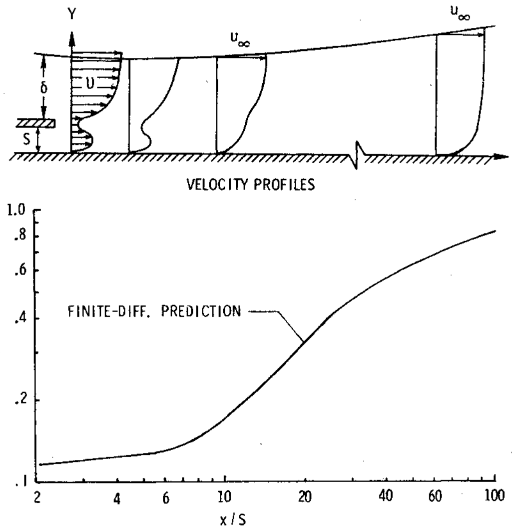

Fig. 1 Velocity development and skin friction behavior downstream of a single slot.

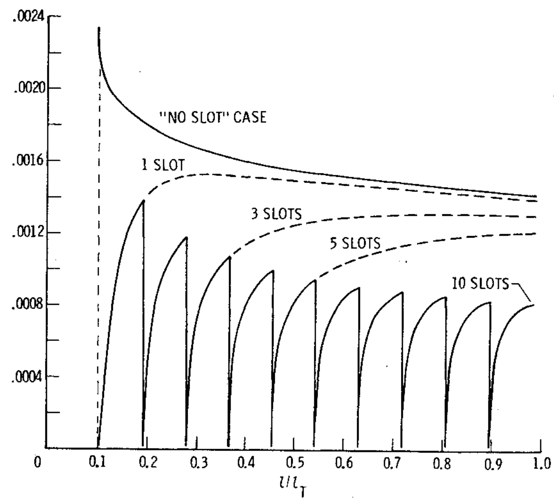

Fig. 2 Skin friction reduction with slot injection, $S=7.46$ cm $(u/u_\infty)_{max}=0.34$.

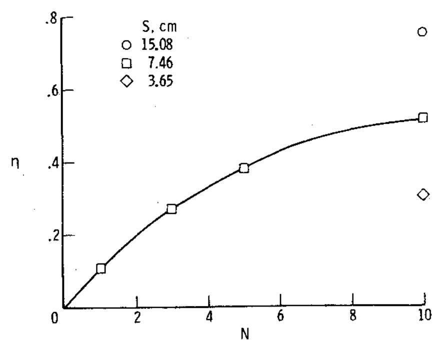

Fig. 3 Skin friction reduction effectiveness as a function of number of slots.

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8 was used to calculate the boundary-layer characteristics up to the first slot, assuming a fully developed turbulent boundary layer from the nose; this boundary-layer velocity profile was then combined with estimated slot exit velocity profiles having a shape similar to those measured in Ref. 4. The resultant velocity profile was input to the slot injection code of Ref. 6. The slot to freestream total temperature ratio was assumed constant and equal to 0.99.

The numerical finite-difference method of Ref. 6 was modified to include multiple slot injection. The effect of one, three, five and ten slots on the fuselage skin friction drag was investigated. Figure 1 shows schematically the velocity profile development downstream of a single tangential slot. In all cases the first slot was located at $x = 0.09$ with the spacing between the slots being 0.09. The effect of slot height (S) was studied for the ten-slot case only; slot heights of 3.65, 7.46, and 15.08 cm were investigated with the boundary-layer thickness (δ) at the first slot equal to 3.61 cm. The slot lip thickness was held constant at 0.16 cm. The input slot velocity profiles for the different slot heights were scaled by the heights of the slot; therefore the actual slot mass flow was proportional to S.

Results and Discussion

The local skin friction coefficients (C_f) obtained downstream of one, three, five, and ten slots (for $S = 7.46$ cm and the ratio of maximum slot velocity to stream velocity (U/U_∞) equal to 0.34) are compared with the local skin friction coefficient on the fuselage without slots ($C_{f,0}$) in Fig. 2. The C_f reduction with only one slot is significant. The beneficial effect of the slot injection is most pronounced immediately downstream of the slot exit and diminishes with increasing surface distance (ℓ) downstream from the slot (ℓ_T is the surface distance over the entire fuselage); this occurs because in the near slot region the wall friction is influenced only by the slot flow while further downstream mixing between the high momentum boundary-layer flow and the relatively low momentum slot flow increases the wall shear. The asymptotic level of skin friction (with injection) approaches a value which is less than that for no slots at moderate downstream distances. This final level depends among other things on the number of injection slots (N).

The benefit of slot injection for C_f reduction is more meaningful in terms of total or average skin friction. The average skin friction coefficient is defined as

$$C_F = \frac{1.0}{\Delta\ell} \int_{\ell_s}^{\ell_T} C_f d\ell$$

where ℓ_s is the surface distance to the first slot and $\Delta\ell$ is the difference between ℓ_s and ℓ_T. The ratio of the reduction in average skin friction ($C_{f,0} - C_F$) to the average skin friction with no injection ($C_{f,0}$) is here defined as the skin friction reduction effectiveness (η).

$$\eta = (C_{F,0} - C_F)/C_{F,0} = 1.0 - \left(\int_{\ell_s}^{\ell_T} C_f d\ell \Big/ \int_{\ell_s}^{\ell_T} C_{f,0} d\ell \right)$$

Figure 3 shows η as a function of N for $S = 7.46$ cm. The values of η for 10 slots with S equal 3.65 cm and 15.08 cm are also shown in Fig. 3 to illustrate the improvement in η with increased S and corresponding mass flow. It is obvious from Fig. 3 that large reductions ($\simeq 50\%$) in viscous drag are available through the use of slot injection systems.

The results shown in Figs. 2 and 3 suggest that the skin friction reduction (η) is improved by increasing the number of injection slots but at a diminishing rate (for constant slot spacing, Fig. 3). One probable reason for this is that slot location is very important; for the present study, the most forward slot is the most effective and the most rearward slot is the least effective. Two advantages of a forward slot location in the present study are: 1) local $C_{f,0}$ is high; and 2) δ is small [C_f reduction is improved at low values of δ/S (Refs. 9 and 10)]. A forward location for slot injection offers the obvious additional advantage that drag reduction occurs over a large area of the aircraft. This effect of slot location is illustrated by the following comparison from Fig. 3; consider the case of 10 slots with $S = 3.65$ cm compared with the case of 5 slots with $S = 7.46$ cm (the first slot in each case is located at the same position). Although the total mass flow from the five 7.46 cm slots would be approximately the same as that for the ten 3.65 cm slots, the skin friction reduction is 27% greater for the 5 slot condiguration than for the 10 slots (see comparison in Fig. 3).

In summary, the results of the present numerical study indicate that substantial skin friction reductions can be obtained with multiple slot injection on a fuselage shape representative of current long-haul subsonic transports. Although the results are very encouraging, they have not been experimentally validated. Systems penalties for collecting, ducting, and injecting the slot air have not been included and will significantly reduct the total available drag reduction. However, optimization of the slot geometry and turbulence control techniques may provide even greater skin friction reductions to help compensate for system losses. In addition, laminar flow control on the wings may provide a viable, low loss, air source for slot injection on the fuselage.

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Supersonic Inlet Contour Interpolation

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Nomenclature

M = design Mach number (freestream)
p = surface static pressure

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