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Applicability of the Independence Principle to Subsonic Turbulent Flow over a Swept Rearward-Facing Step

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Introduction

WITHIN a few years of each other, Prandtl,[1] Struminsky,[2], Jones,[3] and Sears[4] concluded that for yawed laminar incompressible flows the streamwise flow is independent of the spanwise flow. However, when the flow is turbulent, Ashkenas and Riddell[5] and Bradshaw[6] have reported that the "independence principle" (named by Jones) does not apply to yawed flat plates. Alternatively, on the basis of experiment, Young and Booth[7] and Altman and Hayter[8] have indicated that this principle is valid for the fully developed, turbulent boundary layer on yawed infinite cylinders. Theoretically, the Reynolds stress terms in the turbulent boundary-layer equations couple the spanwise and chordwise equations, precluding an independent solution.[9,10] However, for flow over finite geometries at small sweep angles (Λ), with corresponding small values of spatial spanwise velocity and derivatives, the "independence principle" may be applicable to many turbulent flows. As the sweep angle is increased, a sweep angle ("Λ_{crit}") is reached which defines the interval over which the "independence principle" is valid. The present results indicate the magnitude of Λ_{crit} for subsonic turbulent flow over a swept rearward-facing step.

Discussion

The present experiment was conducted in the NASA Langley subsonic low-turbulence open-loop wind tunnel. Splitter-plate models with step heights (h) of 0.32, 0.79, 1.27, and 2.38 cm and sweep angles of 0, 15, 30, 38, 45, and 60 deg were tested. A trip wire located 5.1 cm aft of the leading edge of the splitter plate insured the presence of a 2-cm thick turbulent boundary layer at the step. The Reynolds number (based on the distance at midspan between the leading edge and the step) varied from 7×10^5 to 2×10^6 ($11<V_\infty<32$ m/s).

Reattachment distance (R) data were obtained from oil flow patterns produced using the oil drop method. Visualization of the surface flow direction in the separated flow region downstream of a rearward-facing step is usually extremely difficult using the oil drop method because of the small magnitude of the surface shear stresses there. Black oil-based artist's paint thinned with linseed oil was applied to the surface downstream of the step in the form of droplets. Prior to this, a thin film of lightweight oil was spread over the downstream surface which had been painted white to provide a good contrast. The viscosity of the oil used to coat the surface and of the oil-paint mixture was varied until compatible values were identified through a trial-and-error process. If the viscosity of the dyed oil was too high, the droplets would not flow; if too low, the ground carbon particles would not remain in suspension. Similarly, if the

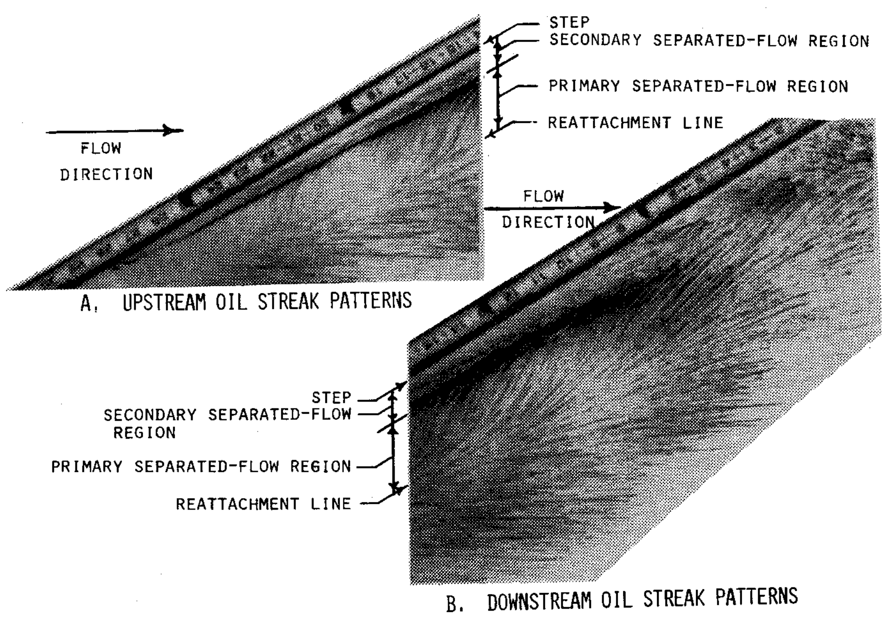

Fig. 1 Surface oil streak patterns ($\Lambda=60$ deg, $V_\infty=21$ m/s, and $h=2.38$ cm).

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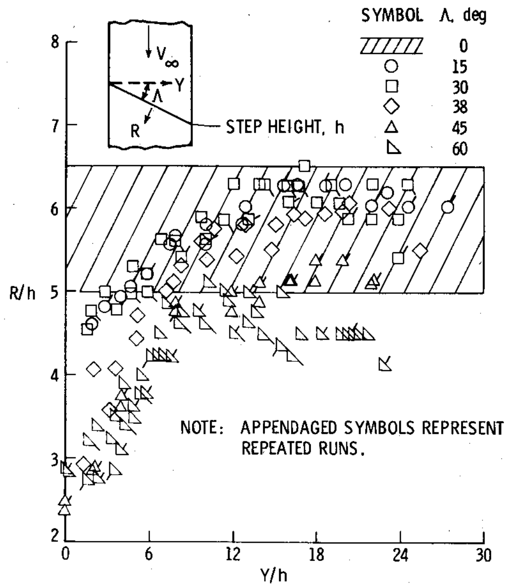

Fig. 2 Reattachment distance vs spanwise coordinate for various sweep angles ($h = 1.27$ cm; hatched area represents two-dimensional results).

viscosity of the coating oil was too high, the droplets would remain stationary. Reattachment distance measurements obtained in this manner were repeatable within ±0.5 step heights. A typical oil flow pattern produced in the manner described is shown in Fig. 1. Additional photographs are presented in Ref. 11.

Reattachment distances measured in planes normal to the step face for $h = 1.27$ cm are displayed in Fig. 2 as a function of the spanwise coordinate. From these data it is possible to determine the range of sweep angles over which the "independence principle" applies (and beyond which sweep effects dominate) by identifying when asymptotic values of the reattachment distance fail to coincide with similar data at lower sweep angles. From Fig. 2 it can be observed that for $\Lambda > 38$ deg ($\approx$"Λ_{crit}") the reattachment distance data fail to follow the trend of the data at smaller sweep angles and generally fall outside the reattachment region (reattachment point fluctuates in the streamwise direction) defined by $\Lambda = 0$ deg. With $h = 0.32$ and 0.79 cm, the effect of sweep is not as great, with the result that $\Lambda_{crit} > 38$ deg. At $h = 2.38$ cm, there is insufficient span for asymptotic values of R to be reached, so the data are inconclusive.

It can be concluded that the "independence principle" is valid up to $\Lambda \approx 38$ deg for $h < 1.27$ cm. The validity of this principle allows the application of two-dimensional analyses (in the proper coordinate system) to the separated flow associated with swept steps for $\Lambda < 38$ deg and $h/\delta < 1$.

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Comparison Between Navier-Stokes and Thin-Layer Computations for Separated Supersonic Flow

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Introduction

IN the numerical simulation of high Reynolds-number flow, one can frequently supply only enough grid points to resolve the viscous terms in a thin layer. As a consequence, a body- or stream-aligned coordinate system is frequently used and viscous terms in this direction are discarded. It is argued that these terms cannot be resolved and computational efficiency is gained by their neglect. Dropping the streamwise viscous terms in this manner has been termed the thin-layer approximation. The thin-layer concept is an old one, and similar viscous terms are dropped, for example, in parabolized Navier-Stokes schemes. However, such schemes also make additional assumptions so that the equations can be marched in space, and such a restriction is not usually imposed on a thin-layer model.

The thin-layer approximation can be justified in much the same way as the boundary-layer approximation; it requires, therefore, a body- or stream-aligned coordinate and a high Reynolds number. Unlike the boundary-layer approximation, the same equations are used throughout, so there is no matching problem. Furthermore, the normal momentum equation is not simplified and the convection terms are not one-sided differenced for marching. Consequently, the thin-layer equations are numerically well behaved at separation and require no special treatment there.

Nevertheless, the thin-layer approximation receives criticism. It has been suggested that the approximation is invalid at separation and, more recently, that it is inadequate for unsteady transonic flow.[1] Although previous comparisons between the thin-layer and Navier-Stokes equations have been made, these comparisons have not been adequately documented.

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