Turbulent Boundary-Layer Relaxation with Application to Skin-Friction Drag Reduction

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Abstract

A LITERATURE survey of turbulent wall layers subjected to abrupt changes in boundary conditions was conducted. Data for the interaction of turbulent boundary layers with a step change in boundary condition (e.g., roughness, pressure gradient, injection, curvature, heat transfer, etc.) indicate that the resulting boundary layer experiences three general types of local modification (i.e., a loss or increase in momentum, a change in inner-region properties and scales, or a change in outer-region properties and scales), with a subsequent downstream relaxation or readjustment of the surface shear or heat transfer which is significantly different for each of the local modifications. Several methods with potential for altering the turbulence production process in the outer region of the boundary layer and reducing the turbulent skin-friction drag over relatively long downstream distances are identified; these include convex longitudinal surface curvature, large-eddy breakup devices, and Emmons-spot alteration.

Contents

Examination of the availabe data for the interaction of turbulent boundary layers with a step change in boundary condition revealed that the downstream relaxation behavior of the surface shear or heat transfer can be significantly different depending on the physics of the perturbation. The relaxation or readjustment downstream of a change in momentum within the boundary layer can either be rapid or slow depending on the amount of momentum added or subtracted and how much of the boundary layer is affected. Turbulent flow modifiers under this category include massive blowing, slot injection, two-dimensional fences either on or off the surface, high-solidity screens, and backward- or forward-facing steps. Changes in wall or outer turbulence structure could also be associated with such momentum deficits. Perturbations or changes in boundary conditions that modify primarily the inner regions of the boundary layer produce relaxation regions that are relatively short (on the order of 20 boundary-layer thicknesses, δ_i, or less). Such modifiers include roughness, moderate or small normal injection, and pressure gradient. Modifications to the outer turbulent flow structures in the boundary layer relax very slowly and the resultant downstream relaxation distances Δx are large and on the order of 40-50 boundary-layer thicknesses or greater. Wall curvature and large-eddy breakup devices constitute the two most obvious modifiers in this category.

For turbulent skin-friction reduction, modifiers in the latter category (i.e., modifiers that alter the outer turbulence structure) are of particular interest if they reduce local skin friction C_f compared to the flat plate C_{f0} or the far downstream equilibrium values $C_{f_{eq}}$ and have slow relaxation rates. References 1-5 show that large-eddy breakup devices (or turbulence "manipulators" or "ribbons") meet this criterion. In fact, the data of Refs. 3 and 4 (Fig. 1) show that relatively thin turbulence manipulators, where t is the manipulator thickness, produce skin-friction reductions of up to 40% over at least 60-80 boundary-layer thicknesses.

Another technique that produces results similar to large-eddy breakup devices and may be a very attractive alternative is that of convex curvature. Figure 2 presents data downstream of both short and relatively long regions of wall curvature. An analysis of the convex curvature data, e.g., Refs. 6-14, indicates that convex curvature having radii of curvature R less than 100 boundary-layer thicknesses destroys the outer turbulence scales and reduces skin friction by as much as 40-50% provided the convex curvature is applied correctly. The curvature must be applied over a surface distance l on the order of 15 boundary-layer thicknesses at a position downstream of transition in fully turbulent flow. Note in Fig. 2b that the data for convex curvature applied over 26 boundary-layer thicknesses either has not apparently begun to relax or has rapidly attained a "new" low-drag equilibrium condition.

An analysis of convex curvature, large-eddy breakup, and Emmons-spot data[15,16] provides insight into a third possibility for altering the outer flow structures and reducing skin-friction drag, i.e., the novel idea of altering the Emmons-spot formation by producing nearly "instantaneous transition." Wygnanski[15] and Zilberman et al.[16] showed that the large outer-flow structures in the turbulent boundary layer are remnants of the Emmons spots found in the transition process, at least for momentum-thickness Reynolds numbers less than 10^4. Simon et al.[12] obtained heat-transfer data which indicate that when convex curvature is applied in a transitional flow region (before the outer structures are fully formed by the Emmons spots), the downstream relaxation is much faster than when the curvature is applied in the fully developed turbulent flow. Corke et at.[3] suggest that the reason their turbulence manipulators reduced the skin friction

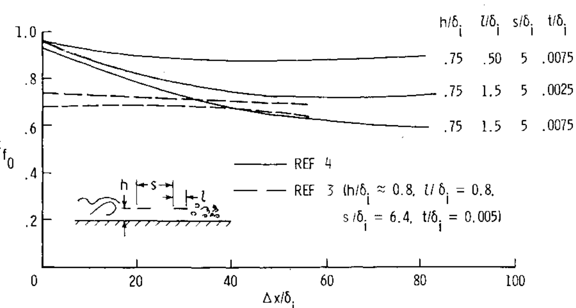

Fig. 1 Relaxation of wall shear downstream of large-eddy breakup devices in low-speed turbulent boundary layers.

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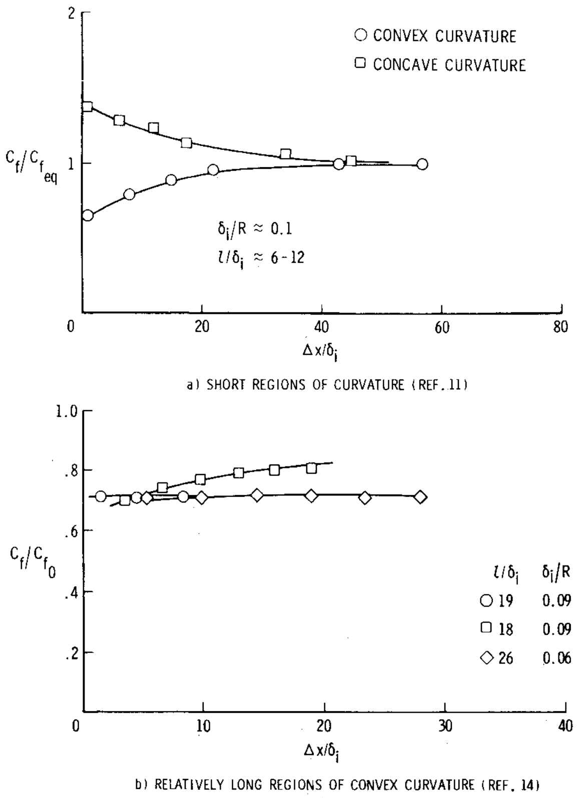

Fig. 2 Relaxation of wall shear downstream of wall curvature.

for large downstream distances is that the manipulators altered the outer large scales which were remnants of the Emmons-spot transition process and prematurely aged the resulting boundary layer. Therefore, it would appear that an effective way to alter the outer-flow structure might be to alter the formation of the Emmons spots directly by producing nearly "instantaneous transition." Work at California Institute of Technology[17] indicated that when two artificially produced spots interact with each other their resulting turbulence intensity is reduced significantly; this suggests that one method of altering the spot formation might be to artificially generate, near a Strouhal number of 1, a row of closely spaced (spanwise) small spots that would interact immediately with each other. This idea is now being worked on by several research institutions including NASA Langley.

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