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Technical Notes

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Drag Reduction in Accelerating Flow

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Introduction

DRAG reduction in turbulent flow continues to be an interesting and challenging problem due to its importance in practical applications. When the surface friction is dominant, drag reduction must be aimed at the reduction of the surface shear stress. When the form drag is induced as a result of separation, drag reduction must be aimed at both preventing separation and decreasing surface friction. Considerable interest and efforts have been focused on this area within the last 15 years. Various devices and techniques have been suggested for reducing the surface friction. These include large eddy breakup,[1] riblets,[2] compliant surfaces,[3] wavy walls,[4] and other surface modifications. Since the mechanisms of turbulence are only partially understood, one can only achieve this purpose on a trial basis.

A recent effort on the study of turbulent flow through perturbation of the Navier-Stokes equation was carried out on the basis of the fractal concept.[5] A set of equations was derived that in turn hinted that the suppression of the growth of the turbulence kinetic energy near the wall can be realized. Solid walls of quasisine wave geometry with elemental minimal surface for accelerating flows can be applied for such a purpose (Fig. 1).

Wind-tunnel tests have been carried out to explore the validity of this conjecture. A wind tunnel of 250-mm-square test section was equipped with an insert to produce a flow with favorable pressure gradient (Fig. 2). Turbulence tripping was applied at the entrance of the tunnel. First, a smooth flat plate of 400 × 250 mm was mounted at the test section, and the electronically monitored and controlled drag balance produced the results as shown in Fig. 3 where the data were least-square fitted (LSF) into a curve. The Reynolds number Re was based on an approximate length of 1.3 m that was the distance from the entrance of the tunnel to the centerline of the plate, and it may be varied by changing the velocity of approach. The flat plate was then replaced by a plate covered with a plastic film of the previously described pattern (Fig. 1). The test results under the same condition of accelerating flow are presented in Fig. 4 and again in Fig. 5 when these results are normalized against the results obtained without the plastic film. Reduction in drag under the accelerating flow condition obviously has been realized. A 50% reduction in C_d has been observed at the approaching flow velocity $V = 60$ m/s, and

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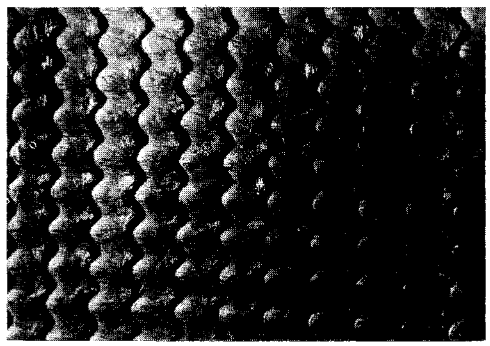

Fig. 1 Surface pattern for drag reduction in accelerating flow.

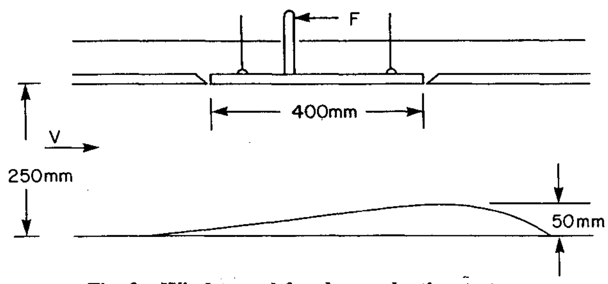

Fig. 2 Wind tunnel for drag reduction test.

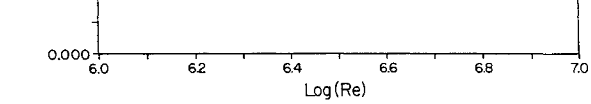

Fig. 3 C_d vs Re of a smooth flat plate in accelerating flow.

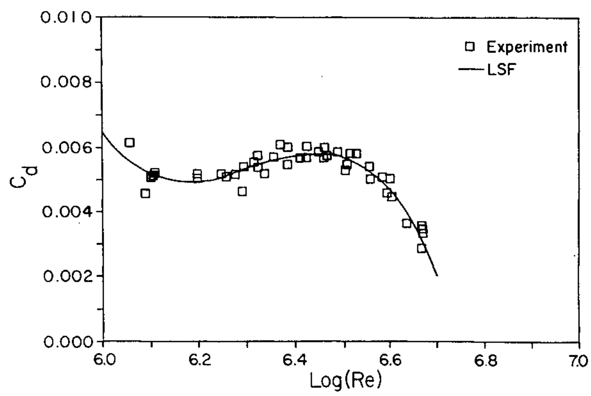

Fig. 4 C_d vs Re of a flat plate with surface pattern in accelerating flow.

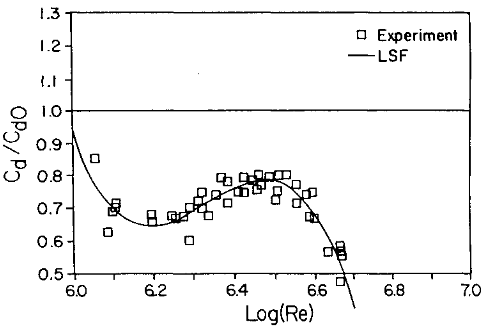

Fig. 5 C_d/C_{d0} **vs** Re **indicating drag reduction.**

this trend of reduction continues at even higher V values. In addition, it is the experience of the first author that this surface pattern for drag reduction is still effective for compressible cascade flow at $M = 0.9$. Studies with decelerating external flow are in progress and results will be presented when they become available.

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Outflow Boundary Conditions Using Duhamel's Equation

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Introduction

MOST computational fluid dynamics (CFD) problems are solved assuming that the solution domain boundaries are either in a uniform stream or at a solid surface. For boundaries in a uniform stream that is at a known velocity and angle of attack, boundary conditions derived from one-dimensional characteristic theory can be applied in a relatively straightforward manner. However, this is not true for boundary conditions in locations where there are flow gradients present or where the flow is unsteady.

Nonreflecting boundary conditions have been developed as a promising means of applying general boundary conditions at an outflow. These boundary conditions prevent the reflections of outgoing waves back into the computational domain and also eliminate incoming waves, details of which are unknown since they originate from outside the domain. However, nonreflecting boundary conditions are only accurate for a limited subclass of flowfields. For instance, both Hedstrom[1] and Thompson[2] noted that these boundary conditions will be inaccurate for problems where the flow should be influenced by incoming waves. The error may be increased for viscous, subsonic, or incompressible flows, as the boundary conditions are derived from the hyperbolic Euler equations, and the loss of information about incoming waves at the boundary will have a greater effect on the interior flowfield.

Although some errors may be expected, nonreflecting boundary conditions provide one of the few options currently available for treating the outflow of unsteady nonuniform flows. In Ref. 3, Thompson's[2] multidimensional boundary condition formulation is extended to curvilinear coordinates and applied to subsonic flows with a wake structure that passes through the outflow boundary. It is concluded that nonreflecting boundary conditions are not adequate for flow in which the upstream influence of the flow outside the computational domain is significant, for example, in vortex shedding from a cylinder.

In the present Note, an alternative to nonreflecting boundary conditions is proposed and is applied to unsteady transonic potential flow about an airfoil. This approach is based on a time linearized version of the equations, but a representation of all other nonlinearities is retained in the model. In this study, it is found that adequate results could be obtained with a downstream boundary at 2% of the extent necessary for conventional nonreflecting boundary conditions. The ideas described here may be extended to treat the Navier-Stokes equations. If such an extension proves as accurate as the case presented here, then the computational domain for complex problems could be reduced significantly, with a corresponding increase in efficiency of the computation, either through reduced computer time or improved resolution.

Analysis

In the following discussion, the interior and exterior domains refer to the regions in the interior of the computational domain, where the body resides, and the region exterior to the computational domain, respectively.

If a particular flow is started from zero, then the flow in the exterior domain is exact until waves from the disturbance in the interior domain cross the boundary between the domains. If true nonreflecting boundary conditions could be devised, then the outflow boundary condition might be correct if the computation were time accurate. An error or an ambiguity in the boundary conditions, due to approximations in the formulation, can give rise to a nonphysical flow in the exterior domain and, ultimately, in the interior domain because of incoming waves. A principal difficulty is in finding an analytic relationship that will give the correct boundary conditions for the governing equations. The progress[3] in nonreflecting boundary conditions shows that finding a true two-dimensional boundary condition that can represent, accurately, incoming waves is beyond the present state-of-the-art. The present work is concerned with an alternative formulation of outflow boundary conditions and is based on the following facts:

1) If the solution is started from a zero disturbance state, with a zero disturbance boundary condition on the far-field

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