Vortex Unwinding in a Turbulent Boundary Layer

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Nomenclature

c = chord of vortex generators
h = height of vortex generators
s = spanwise spacing of vortex generators
t = thickness of vortex generators
U = local x component of velocity in boundary layer
U_e = boundary-layer edge velocity
x = longitudinal (streamwise) coordinate
y = vertical coordinate
z = spanwise coordinate
α = angle of incidence of generators (measured from centerline)
δ = boundary-layer thickness (y at $U/U_e = 0.995$)

Introduction

THE ability to control vortices in a turbulent boundary layer is of interest in areas such as noise reduction, flow separation, heat transfer, wall turbulence control, and perhaps even drag reduction.[1] Specific examples include the possible alleviation of turbulence in wall flows by using streamline curvature engendered by longitudinal vortices and the mitigation of downstream effects of horseshoe vortices typically generated in junction regions. If, in the first example, a set of longitudinal vortices could be generated and then subsequently removed at some distance downstream, the possibly beneficial effects of streamline curvature on wall flows could be studied without the need of surface curvature. In the latter example, the cancellation of horseshoe vortices could reduce the submarine signatures and increase the propulsive efficiency of rear propulsors. The vortex removal technique investigated herein is termed vortex cancellation or, more specifically, vortex unwinding. While vortex cancellation refers to the removal of a vortex, vortex unwinding refers only to the use of a downstream longitudinal vortex with, for example, a positive circulation set to intersect and eliminate an incoming upstream vortex with opposite (e.g., negative) circulation.

Prior work in the area of direct control of vortices by vortices that pertains to this experiment is best exemplified by Refs. 2-4. Reference 2 describes the only known previous attempt at direct vortex unwinding. In this report, airfoils were used to create the initial and downstream (unwinding) vortices and a tuft grid was used to measure the success of the unwinding method. The author also presents a first-order theoretical treatment of the problem to predict the strength of the unwinding vortex required to cancel the incoming vortex. While this study was limited (in that only one downstream station was examined with the tuft grid), it does suggest that vortex unwinding is a viable means of vortex cancellation in the freestream. Another attempt at vortex cancellation[3] employed the method of vortex merging for the purpose of alleviating the wake vortices of aircraft. In this method, a vortex is generated with the same sense of rotation and at approximately the same longitudinal station as the wing-tip vortex. Downstream in the wake, the vortices merged and formed a larger (albeit weaker) vortex that dissipated more quickly and was therefore less of a hazard to following aircraft. Reference 4 documents an attempt at vortex cancellation in a turbulent boundary layer. The investigators attempted to remove the spanwise variations in a wind tunnel boundary layer by using blocks, placed near the leading edge of the plate, to create corner vortices that would counteract the local direction of swirl. They were unsuccessful with this technique and suggested that vortex cancellation was not a reasonable method of vortex control in a turbulent boundary layer.

In the present experiment, the vortex unwinding method is studied as a means of performing vortex cancellation in a turbulent boundary layer. As well as having possible applications in the areas of wall turbulence control and horseshoe vortex alleviation, this preliminary study is intended to determine the feasibility of extending the work done in Ref. 1 to a system of vortices in a turbulent boundary layer and to show that vortex cancellation (via vortex unwinding) is a viable means of vortex control in that regime.

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Results and Discussion

The experiment was performed in the Langley 2×3 ft Low-Speed Boundary-Layer Channel at a velocity of 40 m/s. A nominally two-dimensional turbulent boundary layer was developed on a splitter plate 5.8 m long and 0.91 m wide with a 30 grid sandpaper trip at the leading edge. Mean velocity (U component) boundary-layer measurements were made with a flattened pitot tube referenced to the local static pressure. Vortex generators designed from Ref. 5 were used to produce an initial set of corotating vortices in the turbulent boundary layer. Corotating vortices were chosen for this experiment because they tend to remain in the boundary layer in an ordered fashion, as opposed to counter-rotating vortices that migrate out of the boundary layer. The vortex generators were placed at the $x = 1219$ mm station (Fig. 1) where the reference boundary-layer thickness was $\delta = 20.5$ mm. The generators were set at an angle of $\alpha = 3$ deg with a spanwise spacing of $s = 3.96\ \delta$ (above the Pearcey criteria[6] for "independent development") and with dimensions $h = 20.32$ mm, $c = 40.64$ mm, and $t = 0.25$ mm. Figure 2 shows the spanwise isotachs (lines of constant velocity) of the undisturbed two-dimensional boundary layer at $x = 2438$ mm. Figure 3 shows the isotachs at the same longitudinal station with the vortex generators in place at $x = 1219$ mm. This distinct pattern was observed to last until the end of the measurable test section at $x = 4572$ mm, thus insuring sufficiently strong vortices.

Once the vortex flowfield was extensively surveyed, the vortex unwinders were positioned on the splitter plate at $x = 1625$ mm. By an iterative process (totaling 26 configurations), the z locations, planform, and the angle of the unwinders were optimized. As a first cut, the spanwise positions of the vortex cores were estimated to be located in the areas between the upswept and downswept isotachs. This initial estimate proved to be very near the optimum because at $x = 1625$ mm, only 20 δ downstream of the generators, the vortices were very distinct and the area in question was not large.

Several different planforms were tried, but none seemed superior to the rectangular planform. The initial height of the unwinders was chosen to allow for some upward movement of the vortex with boundary-layer growth. The initial unwinder angle was chosen at -3 deg and reduced until a final value of -1.5 deg was reached. The smaller angle is attributed to the viscous dissipation of the initial vortices strength. Thus, the final configuration was a rectangular flat-plate planform with dimensions $h = 22.86$ mm, $c = 45.72$ mm, $t = 0.25$ mm, and $\alpha = -1.5$ deg. Figure 4 shows the reduction in the amount of spanwise variation in the boundary layer at $x = 2438$ mm due to the placement of the unwinders.

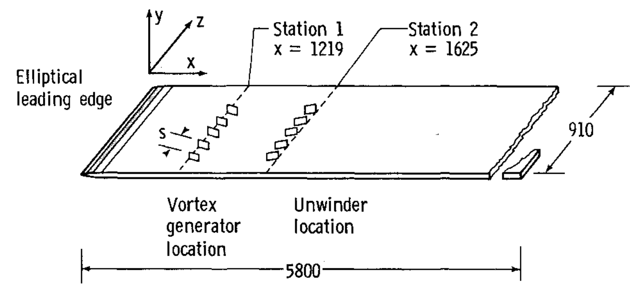

Fig. 1 Splitter plate showing generator/unwinder arrangement (all dimensions in millimeters).

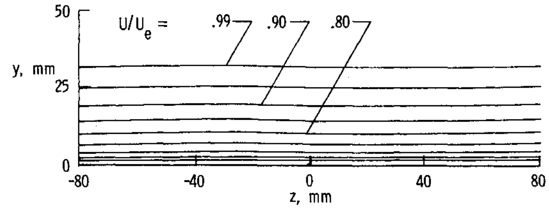

Fig. 2 Spanwise isotachs of undisturbed boundary layer, $x = 2438$ mm.

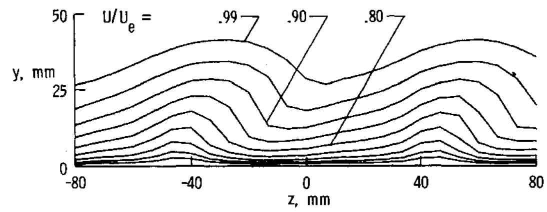

Fig. 3 Spanwise isotachs with vortex generators, $x = 2438$ mm.

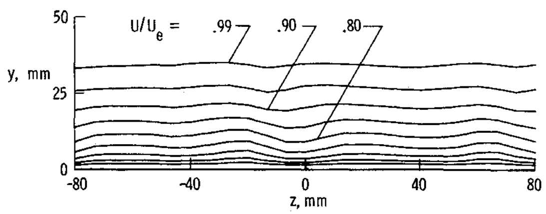

Fig. 4 Spanwise isotachs with generators and unwinders, $x = 2438$ mm.

Although this configuration was not a true optimum (in that the isotachs in Fig. 4 are not identical to the nominally two-dimensional case), the optimization process was halted for several reasons. Primarily, the major improvement in the boundary-layer variation is believed to be a sufficient indication of the feasibility of vortex unwinding in this situation. Several of the points raised in Ref. 2 were found to apply in the boundary layer, e.g., correct spanwise position is important and various levels of unwinding can be achieved depending on unwinder strength. In fact, in this experiment, the initial unwinder angle of -3 deg actually reversed the entire spanwise flowfield. Second, any further optimization will require more detailed measurements of the vortices strengths and positions. In contrast to Ref. 2, where the unwinder angle needed to be accurate only to within 1 deg, the present configuration showed sensitivity to changes of at least 0.25 deg. The final unwinder configuration, while close to the true optimum, was actually slightly overpowering. However, since this setting so greatly reduced the spanwise variations, it is reasonable to assume that given time, and perhaps more detailed measurements, the vortices could be completely removed.

Conclusion

In this Note, the feasibility of vortex unwinding in a turbulent boundary layer has been demonstrated. While the true optimum unwinding configuration was not reached (i.e., the return to the nominally two-dimensional case), sufficient reduction in the isotach variation was achieved to verify the usefulness of this technique in turbulent boundary-layer vortex control. It is suggested that more detailed measurements of vortex strength and position will improve the optimization process and increase the amount of vortex unwinding. It should be noted that most of the applications suggested in this Note will benefit from vortex reduction as well as from complete vortex unwinding.

References

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Spanwise Pressure Distribution on Delta Wing with Leading-Edge Vortex Flap

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Nomenclature

A	= aspect ratio
$b(x)$	= local wing span
$\bar{c}$	= aerodynamic mean chord
c_r	= root chord
C_D	= drag coefficient
C_L	= lift coefficient
C_m	= pitching moment coefficient
D	= drag
FVS	= free vortex sheet
L	= lift
x,y,z	= body axis coordinates
α	= angle of attack
δ	= flap angle normal to hinge
Λ	= leading-edge sweep angle

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