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Interaction of a Longitudinal Vortex with a Three-Dimensional, Turbulent Boundary Layer

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Abstract

THE distortion of a pressure-driven, three-dimensional boundary layer by an embedded longitudinal vortex was studied experimentally. The peak vorticity and secondary velocities were found to decay much more rapidly in a three-dimensional boundary layer than in a similar two-dimensional layer. The distortion of the boundary layer was strongly dependent on the sign of the vortex.

Contents

Longitudinal vortices are used frequently to manage separation on aircraft surfaces and in internal flow passages. Such vortices when embedded in a turbulent boundary layer cause large distortion in both the mean velocity and turbulent stress fields. There have been extensive experimental investigations[1,2] examining vortex/boundary-layer interactions in support of turbulence model development for these complex but important flows. The previous detailed studies have all been conducted in flows where a longitudinal vortex interacts with an otherwise two-dimensional boundary layer. However, in virtually all of the applications, the boundary layer of interest is three-dimensional, the flow on a swept wing with attached vortex generators being the classic example. Three-dimensional boundary layers have distributed mean flow longitudinal vorticity which may interact with the rolled up longitudinal vortex. It will be shown here that this interaction leads to substantial differences in the development of the vortex and the boundary layer mean velocity field. Full details of the experiment and results are outlined in Ref. 3.

The experiments were conducted in the attached three-dimensional boundary-layer apparatus used by Anderson and Eaton.[4] A two-dimensional boundary layer with a momentum thickness Reynolds number of 3750 at a freestream velocity of 16.3 m/s approached a 60-deg included angle wedge which split the boundary layer and deflected it in the spanwise direction. The flow near the wall turned through a larger angle than the freestream creating strong skewing across the boundary layer. The resulting three-dimensional boundary layer contained distributed longitudinal vorticity of negative sign in the outer layer and concentrated positive vorticity in a thin layer adjacent to the wall. A longitudinal vortex was introduced at the end of the two-dimensional development section using a 2-cm high by 4.7-cm long half-delta vortex generator mounted to the wall. Both signs of the longitudinal vortex were investigated; case 1 was a vortex with negative circulation, and case 2 was a vortex with equal size and strength but the opposite sign. An embedded vortex does not follow a freestream streamline due to the effect of the vortex image in the wall. Therefore, we selected the vortex generator position for each case so that the vortex center would coincide with Anderson and Eaton's selected streamline midway through the three-dimensional test section.

Measurements of all three components of the mean velocity field were obtained with a computer-controlled five-hole probe using the techniques described in Ref. 2. Redundant mean velocity measurements and turbulent stresses were measured using a rotatable x-array hotwire.

The measurements show that a longitudinal vortex dies out much more quickly in a three-dimensional boundary layer than in a similar two-dimensional boundary layer. Figure 1 shows the peak longitudinal vorticity for the two cases compared to a case where a nearly identical vortex was embedded in a two-dimensional boundary layer.[2] The peak level decays similarly for the present two cases, but decays much more slowly in a two-dimensional boundary layer. The reason for the rapid attenuation of the core vorticity is apparently straining and diffusion in the crossflow plane. The strong gradient of the crossflow velocity component stretches and tilts the vortex into a configuration that is apparently subject to stronger vorticity diffusion.

Strong differences between the two cases show up in the development of the mean velocity perturbation. Figure 2 shows contour plots of the mean axial velocity at a station 51 cm downstream of the vortex generator. In case 1, the vortex induced perturbation has already decayed substantially. However, the contour plot for case 2 shows large distortions with a substantial region of low momentum fluid lifted away from the wall. The difference in the mean velocity field also leads to striking differences in the turbulence field with much higher turbulent kinetic energy and shear stress in case 2.

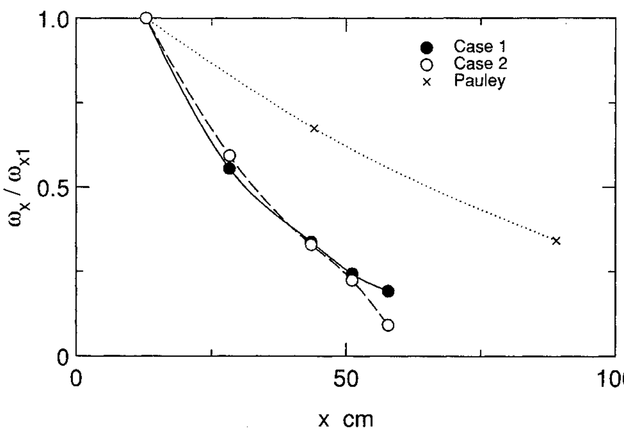

Fig. 1 Axial variation of peak vorticity compared to data from Pauley and Eaton.[2]

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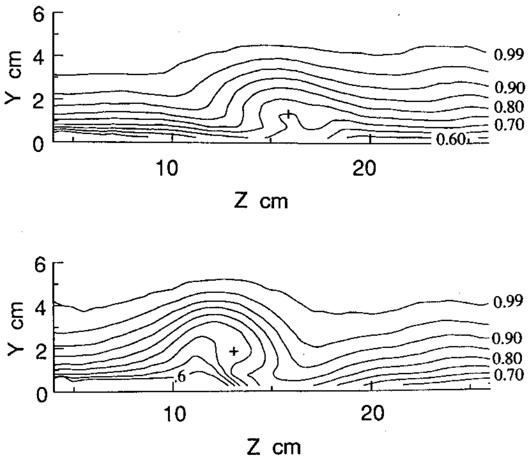

Fig. 2 Contours of the axial velocity measured 51 cm downstream of vortex generator. Velocity values normalized by the local freestream velocity. Top graph: case 1. Bottom graph: case 2.

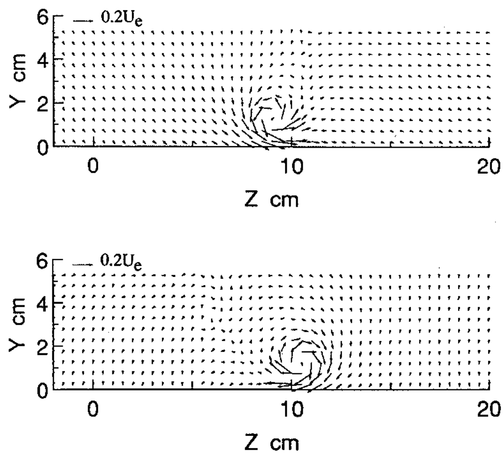

Fig. 3 Vector plots showing secondary velocities measured 13 cm downstream of vortex generator. Top graph: case 1. Bottom graph: case 2.

The differences between the two cases are caused by the interaction between the crossflow induced by the flow turning and the vortex-induced crossflow. Figure 3 shows the secondary velocity measurements for the two cases at the first measurement station, 13 cm downstream of the vortex generator. Examining case 2 first, we see that the crossflow induced by the wedge is opposed near the wall by the vortex-induced crossflow resulting in crossflow separation around $Z = 8$ cm. The resulting strong vertical velocity component carries low momentum fluid away from the wall creating the large deficit region seen in Fig. 2. In case 1, the wedge-induced and vortex-induced crossflows are in the same direction near the wall and crossflow separation is suppressed. Low momentum fluid which passes under the vortex is swept away in the positive Z direction by the overall crossflow.

The present results suggest that accurate prediction of realistic vortex/boundary-layer interactions may be even more difficult than was previously believed. The position and strength of the crossflow separation are critical in determining the overall flow development. Prediction of this would require more accurate prediction of the crossflow velocity profile than has previously been achieved.

Acknowledgments

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