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Three-Dimensional Structure of Straight and Curved Plane Wakes

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ABSTRACT

Although the plane wake is marked by the formation of strong spanwise vortices, the initially two-dimensional Karman-like vortices soon develop a three-dimensional structure in the form of secondary streamwise vortices. So far, this streamwise vortex structure has been studied mostly through flow visualization and at relatively low Reynolds numbers. The primary objective of the present program was to investigate the origin and evolution of the three-dimensional structure of straight and curved plane wakes at relatively high Reynolds numbers ($Re_b = 28{,}000$) through detailed measurements of the mean and turbulent properties at several streamwise locations.

The experiments were conducted in three phases. In the first phase, the development of a straight plane wake was investigated. In the second phase, the effects of imposed streamwise curvature on the wake development were examined. The streamwise curvature was of constant radius and *very* mild in terms of the curvature ratio ($b/\overline{R} < 2\%$). In both the first and second phases, the role of initial conditions was examined in wakes generated from both untripped (laminar) and tripped (turbulent) initial boundary layers. In the third phase, the effects of injecting streamwise vorticity and the effects of increased Reynolds number on the tripped wake structure and development were investigated.

In the straight untripped wake, large-scale spanwise variations were observed. This spanwise variation manifested itself in the form of "pinches" and "crests" in the contours of mean velocity and Reynolds stresses. Well-organized spatially-stationary streamwise vorticity was generated in the near-field region in the form of quadrupoles, to which the relatively large spanwise variations in the mean velocity and Reynolds stress distributions were attributed. The mean streamwise vorticity decayed on both sides of the wake at approximately the same rate and appeared to have fully decayed by the far-wake. Despite the decay of the mean streamwise vorticity, the large-scale spanwise variations persisted into the far-wake. The effects of tripping the initial boundary layers in the straight tripped case was to remove the large-scale spanwise variation which resulted in the contours of mean velocity

and Reynolds stresses appearing nominally two-dimensional. The two-dimensional appearance was a consequence of spatially-stationary streamwise vortices not being generated in this case, although this does not preclude the generation of temporally-variant streamwise vorticity.

The curved wake cases were affected by the angular momentum instability such that the inside half of the wake was unstable, whereas the outside half was stable. With the initial boundary layers laminar, the curved case exhibited spanwise variations, which were qualitatively similar to those seen in the straight case. Although the mean streamwise vorticity on both sides (stable and unstable) decayed with streamwise distance, the rate of decay on the unstable side was considerably lower than that in the straight case, while that on the stable side was higher. As in the straight cases, with the initial boundary layers turbulent, spatially-stationary streamwise vorticity was not observed. The curvature affected the wake growth and defect-decay rates, but in different ways for each of the two initial conditions. The effects of curvature were also apparent in the Reynolds stress results, especially in the primary shear stress distributions, which showed that the levels on the unstable side were increased significantly compared to those on the stable side with the effect much stronger in the initially laminar wake.

The effects of Reynolds number were examined on the curved tripped wake only. The increase in Reynolds number (from 28,000 to 41,000) did not alter the mean properties of the wake and had no significant effect on the normalized Reynolds stresses. The effects of injecting a single array of streamwise vortices in the straight wake developing from tripped initial boundary layers were to produce large-scale, regular spanwise variations in the near-wake. Although the mean streamwise vorticity decayed relatively rapidly, the wake growth rate and Reynolds stress levels in the far-field region were reduced significantly.

The two-dimensional structure of the wake is qualitatively similar to that of the mixing layer, in that it also consists of spanwise rollers connected by braids. It is therefore expected that the same type of instability mechanisms as in the mixing layer are responsible for the generation of the three-dimensionality. The instability