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Turbulent Flow Measurements in an Idealized Wing/Body Junction

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Abstract

THERE are two mechanisms for the generation of secondary flow. One is generation by Reynolds-stress gradients; a widely studied example[1,2] is flow in the corner of a long, straight rectangular duct. A much more powerful mechanism, which does not rely on viscous or turbulent stress, is lateral skewing of a shear layer, as in the case of the body boundary layer encountering a wing/body or blade/hub junction[3] or flow near the plane wall of a curved rectangular duct.[4] Reynolds-stress-induced secondary flows are slow to develop, and skew-induced secondary flows are slow to be attenuated by Reynolds stresses, but little information about their decay is available.

Measurements of the decay of the skew-induced "horseshoe" vortex in low-speed flow are reported herein. The vortex is found to dominate the corner flow over the full chord length of the wing, a distance from the leading edge of about 50 times the body boundary-layer thickness. The eddy viscosity tensor is highly anisotropic, with large negative regions.

Contents

The measurements were made at an external flow speed of 30 m/s in the simple configuration of Fig. 1, which can be thought of as an idealized wing/body junction. The "wing" consisted of a semielliptical leading edge followed by a slab of constant thickness; the region of generation of secondary flow near the leading edge was not studied in detail (it could be calculated by the inviscid rotational solution technique described by Rubel[5]) and measurements were confined to the region of nearly constant pressure further downstream. Further measurements in the same rig by Mehta (unpublished) show that the vortex diameter and its distance from the body depend to some extent on leading-edge shape. However, for wing sections typical of subsonic aircraft, the skew-induced vortex is likely to dominate the corner flow all the way to the trailing edge. The main effect of an imposed pressure gradient on a streamwise corner vortex is to cause it to wander away from the corner, which was felt to be an unnecessary complication in the present basic experiment. The wing extends between the floor and roof of the wind tunnel, but the effect of the roof on the flow near the floor is thought to be small since, even at the "trailing edge," the ratio of wing boundary-layer thickness to tunnel height is only about 0.16, well below the limit of 0.25 specified in Ref. 6 for the normality of the boundary layer near midspan. Extensive turbulence measurements have been made and are fully reported in Ref. 7. Mean velocity and rms intensity were measured over eight cross-sectional planes, and all second- and third-order products of velocity fluctuations and all three flatness factors were measured at three cross-sectional planes. Raw cross-wire signals occupying approximately 160 km (100 miles) of analog tape track are available for further analysis. (Tabulations of the reduced data are obtainable from the second author on punched cards or magnetic tape.)

Only a few representative results, at the downstream-most station where the secondary flow was weakest, will be presented herein. This station is located at a distance from the leading edge equal to about 50 times the body boundary-layer thickness at the leading edge, i.e., 23 mm. Figure 2 shows the axial velocity contours, of which the outermost defines the

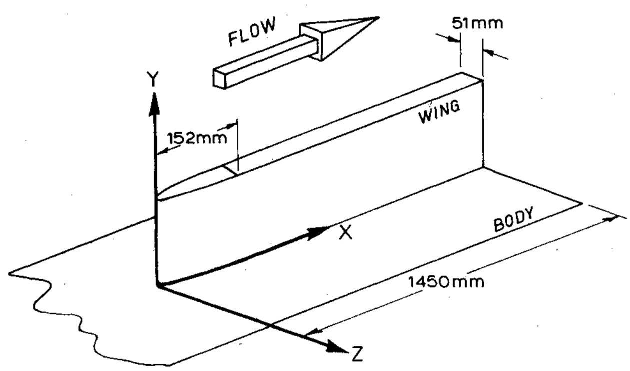

Fig. 1 Idealized wing/body junction.

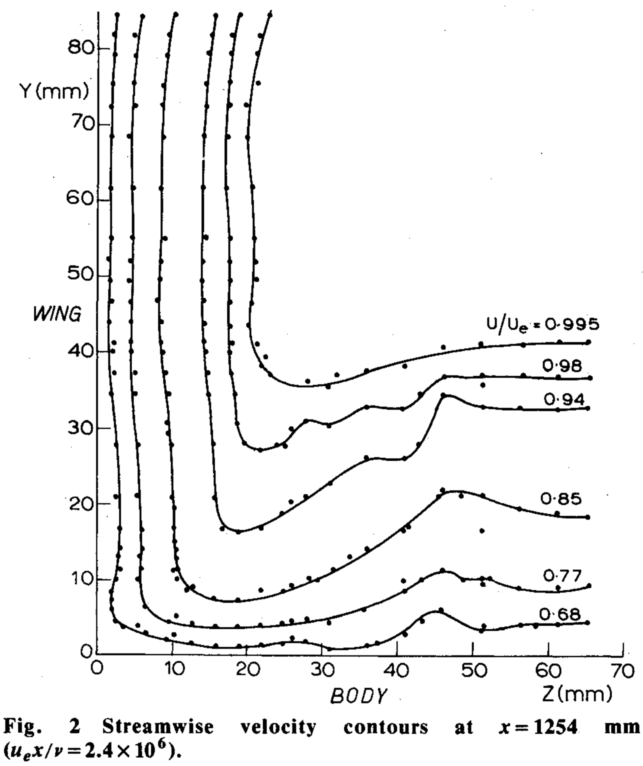

Fig. 2 Streamwise velocity contours at $x = 1254$ mm ($u_e x/\nu = 2.4 \times 10^6$).

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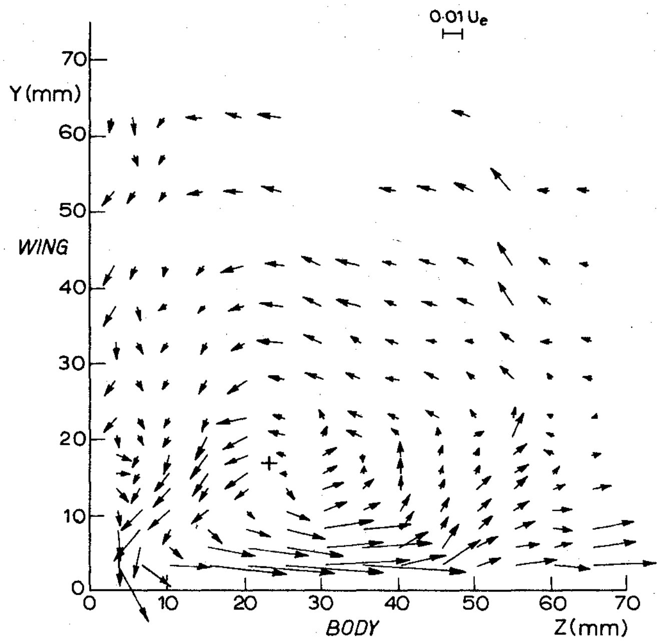

Fig. 3 Secondary flow vectors at $x = 1223$ mm.

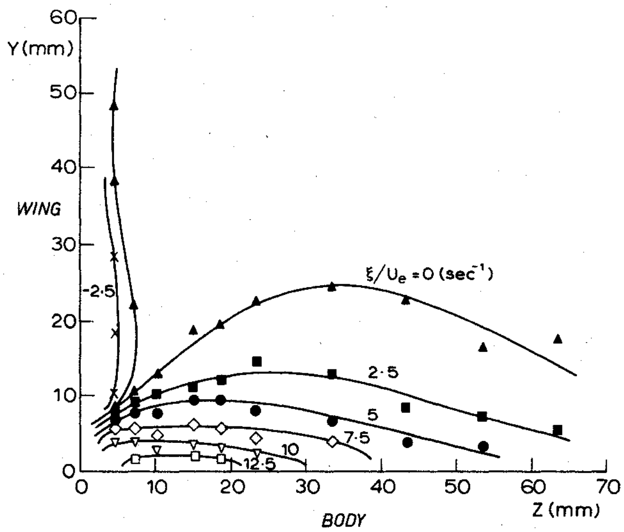

Fig. 4 Contour map of the streamwise vorticity at $x = 1223$ mm.

boundary-layer thickness δ_{995}. The kink in the contours near $z = 45$ mm is qualitatively real and is found at other stations. A logarithmic region is detectable in the mean velocity profiles in the first 10-20% of the shear layer thickness, except for distances from the corner less than about 20% of the shear layer thickness. Figure 3 shows the secondary-flow velocity vectors measured with a crossed hot-wire probe. (An upper bound on the inaccuracy of measurement is provided by the results near $y = 60$ mm, where V is expected to be fairly small, but is still consistent with the main trend.) There is clear evidence of a vortex with its center near $y = 15$ and $z = 25$, with at most a slight trace of a second vortex on the opposite side of the corner bisector. Thus, skew-induced secondary flow still dominates over stress-induced secondary flow even at this large distance from the leading edge. Despite the growth of the boundary layer, the vortex position changes little with streamwise distance. The large values of W between the vortex center and the body surface are noteworthy; this flow up the body seems to be supplied more by longitudinal retardation than by inflow from the wing. Figure 4 shows that, as a result of the large W motion just referred to, streamwise vorticity is a maximum near the body surface and not near the vortex center. This implies that the W-component motion is induced by the Reynolds stresses (set up by the skew-induced vortex) rather than by pressure differences, for in the latter case, the z-wise outflow would have roughly the same streamwise vorticity as the fluid nearer the corner. The region of negative longitudinal vorticity near the wing is the natural effect of the no-slip condition $V = 0$ on the wing surface, and it is interesting that this region is comparatively thick.

The Reynolds stresses $-\overline{uv}$ and $-\rho\overline{uw}$ represent transfer of streamwise momentum in the y and z directions, respectively. We can define eddy viscosities for these two stresses as $-\overline{uv}/(\partial U/\partial y)$ and $-\overline{uw}/(\partial U/\partial z)$. Measurements reported in the backup document show that not only are the two eddy viscosities different, but they become negative over large regions near the corner. For $z < 20$ and $15 < y < 50$, $\partial U/\partial y$ is positive (but small) while $-\overline{uv}$ is negative; for $y < 20$, $15 < z < 30$, $\partial U/\partial z$ is negative, but $-\overline{uw}$ is positive. It seems unlikely that any calculation method based on eddy viscosity would be suitable for this complex flow. The only practical alternative is to use empirical transport equations for all, or nearly all, the Reynolds stresses. Complete balances for the turbulent energy and for the shear stresses $-\overline{uv}$, $-\overline{uw}$, and $-\overline{vw}$ are given in Ref. 7. It is found that in regions where the Reynolds shear stress and the corresponding mean velocity gradient (for instance $-\overline{uv}$ and $\partial U/\partial y$) have opposite signs, the pressure strain term in the Reynolds-stress transport equation, normally thought of as a redistributional "scrambling" term, can actually augment the shear stress. As might be expected from the presence of negative eddy viscosity, the flow is far from local equilibrium, and cross-stream mean and turbulent transport of Reynolds stress is important. Thus, this common type of turbulent flow presents a considerable challenge to the predictor.

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