Downstream Recovery of Turbulence Kinetic Energy in the Wake of a Turbulent Boundary Layer Wing-Body Junction Flow

S. Zimmerman¹, J. Philip¹, N. Marino² and J. Klewicki¹,²

¹Department of Mechanical Engineering
University of Melbourne, Parkville, Victoria 3010, Australia
²Department of Mechanical Engineering
University of New Hampshire, Durham, New Hampshire 03824, USA

Abstract

A multi-sensor hotwire probe capable of simultaneously measuring all three components of the velocity vector [Zimmerman et al. 2017] has been deployed in the wake of a turbulent boundary layer wing-body junction flow. The wing shape—a 3:2 semi-elliptic nose joined to a NACA 0020 airfoil tail—matches that used in a number of existing studies of wing-body junction wake flow (e.g. see the review of Simpson [2001]). Data have been collected in four spanwise/wall-normal measurement planes ranging from 1 to 33 chord lengths behind the trailing edge of the junction. The measurement planes span a domain over which the unperturbed boundary layer would develop from the edge of the junction. The measurement planes are spaced wall-normal positions. The measurement probe effectively simulates three component velocity data were acquired in 8-sensor hot-wire anemometry probe first deployed in the wake of a turbulent boundary layer facility with a flow development length of 72 meters. The scale of the FPF allows achievement of friction Reynolds numbers \( Re_\tau \equiv \delta_{99} u_\tau / \nu \) in excess of \( 10^4 \) without rendering the smallest energetic scales unresolvable by conventional measurement techniques. Streamwise/wall-normal velocity and spanwise vorticity measurements collected at the FPF under ZPG conditions are presented in [3], and three-component velocity and vorticity measurements are presented in [7].

The present data were collected at the Flow Physics Facility (FPF) at the University of New Hampshire. The FPF, characterised in detail by [6], is an open-circuit zero-pressure-gradient boundary layer facility with a flow development length of 72 meters. The scale of the FPF allows achievement of friction Reynolds numbers \( Re_\tau \equiv \delta_{99} u_\tau / \nu \) in excess of \( 10^4 \) without rendering the smallest energetic scales unresolvable by conventional measurement techniques. Streamwise/wall-normal velocity and spanwise vorticity measurements collected at the FPF under ZPG conditions are presented in [3], and three-component velocity and vorticity measurements are presented in [7].

The sheeted obstacle, a “Rood wing”, was placed in the FPF at a 0° angle-of-attack with its leading edge 30.6m downstream of the turbulence trip. A schematic of the in-flow boundary layer and the four measurement planes is shown in figure 1.

Three component velocity data were acquired in \( y-z \) planes at each of the four streamwise \((x)\) measurement stations by means of an 8-sensor hot-wire anemometry probe first described by [7]. Each measurement plane is comprised of a grid of 8 linearly-spaced spanwise positions and 10 logarithmically-spaced wall-normal positions. The measurement probe effectively consists of four independent \( x \)-wire pairs, arranged such that all three velocity and vorticity components may be estimated simultaneously about the centroid of the measurement volume. The present experiments are unique in the downstream fetch of the observations, their quantification of the turbulence kinetic energy, the \( Re_\tau \) of the in-flow boundary layer, and the high resolution of the measurements.

Results

Contours of mean streamwise velocity \( \bar{U} \) normalized by the free-stream velocity \( U_0 \) are shown for each of the four stream-
wise measurement stations in figure 2. Also shown in figure 2 are the differences between $\overline{U}/U_0$ for the junction-flow wake and the unperturbed ZPG boundary layer. The footprint of the secondary flow on $\overline{U}$ is clearly visible at $x/C = 1$, as shown in figures 2(a) and 2(b). The curvature of the $U/U_0$ contours below $y/T \approx 1$ and inboard of $z/T \approx 2$ at this location reflects the mean momentum transport associated with the horseshoe vortex. The negative-oriented mean streamwise vorticity $\Omega_a$ tends to lift low-momentum boundary layer fluid away from the wall in a region bounded approximately by $0.5 \lesssim z/T \lesssim 1.7$, and draws high-momentum fluid toward the wall inboard of $z/T \approx 0.5$. The primary horseshoe vortex may also induce additional streamwise vorticity further outboard, as evidenced by the contours in figures 2(a) and (b) in the region bounded by $z/T \gtrsim 2.5$ and $y/T \lesssim 1$. The wake of the Rood wing above its junction with the wall is also visible in the $x/C = 1$ plane in the form of a momentum deficit in the region bounded by $x/C = 1$ plane. The peak is less distinct (or non-existent) at $x/C = 17.8$ and $x/C = 33$ planes, a high-momentum ‘core’ persists and maintains spanwise inhomogeneity, but weakens in magnitude and appears to spread appreciably only in the $y$ direction. This is consistent with the observations of [1], that the horseshoe vortex ‘legs’ have an approximately constant width beyond $x/C = 5$, and that further spreading is caused primarily by boundary layer growth.

The spanwise spreading of the overall disturbance is apparent in the dependence of the momentum deficit on streamwise and spanwise position. This dependence is represented here through the quantity $\Theta_T$, defined in equations (1) and (2) and plotted in figure 3.

$$\Theta_T = \int_0^T \overline{U}/U_0 \left(1 - \overline{U}/\overline{U}_o\right) dy$$

$$\Theta_T = \frac{\theta_T - \theta_{T,ZPG}}{\theta_{T,ZPG}}$$

Figure 3: Proportional difference in momentum deficit thickness between junction flow wake and ZPG below $y/T = 1$ for (symbols darkest to lightest) $x/C = 1$, $x/C = 8.4$, $x/C = 17.8$, and $x/C = 33.0$.
Figure 2: Mean streamwise velocity contours ((a), (c), (e), (g)) and their difference from unperturbed ZPG case ((b), (d), (f), (h)) for y-z measurement planes at (a), (b): x/C = 1.0, (c), (d): x/C = 8.4, (e), (f): x/C = 17.8 and (g), (h): x/C = 33.0.

Figure 4 shows the mean turbulence kinetic energy $k$ in the junction flow wake as well as the difference in $k$ between the junction flow wake and the unperturbed ZPG boundary layer for the four measurement planes. Low momentum regions (relative to the ZPG case) identified above each exhibit higher turbulence kinetic energy than the comparable ZPG case, while those having higher mean momentum each exhibit lower turbulence kinetic energy. In the regions affected by the secondary flow, this reflects the mixing associated with the horseshoe vortex. High momentum boundary layer fluid drawn toward the wall transports with it lower turbulence kinetic energy, while low momentum fluid ejected away from the wall carries energetic motions associated with the near-wall flow. In the region bounded by $z/T \lesssim 1$ and $y/T \geq 1$ at $x/C = 1$, the high turbulence kinetic energy relative to the ZPG case is reflective of the wake of the wing and not the secondary flow. As with the mean momentum, the ‘core’ of low $k$ initially associated with the secondary flow spreads primarily in the $y$-direction with downstream distance as the boundary layer continues to grow.

Conclusions
Mean velocity and turbulence kinetic energy were acquired in the wake of a turbulent wing-body junction flow via multisensor hot-wire anemometry. These data capture the near-wake characteristics of the horseshoe vortex, as well as its downstream evolution and associated relaxation of the flow field toward spanwise homogeneity. The far wake behind the junction is characterised by higher momentum close to the centerline and lower momentum further outboard. This is the opposite of a typical bluff-body wake, indicating that the transport of momentum associated with the secondary flow dominates over loss of momentum associated with the net drag around the wing within the boundary layer. The momentum deficit behind the wing extends above $y/H = 1$, indicating that the high momentum ‘core’ region does not owe its existence to the low $\delta/H$ ratio of the present experiment. The high momentum core can be seen through the momentum deficit thickness to spread with downstream distance. The momentum deficit thickness at the furthest downstream position ($x/C = 33.0$) varies approximately linearly with $z$. 
Figure 4: Mean turbulence kinetic energy contours ((a), (c), (e), (g)) and their difference from unperturbed ZPG case ((b), (d), (f), (h)) for y-z measurement planes at (a), (b): x/C = 1.0, (c), (d): x/C = 8.4, (e), (f): x/C = 17.8 and (g), (h): x/C = 33.0.

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References