Transverse Vorticity Observations in Large Coherent Structures

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Introduction

An examination of the literature indicates differing ideas about the activity, distribution, and magnitude of the transverse vorticity within the large coherent structures (i.e., organized vortical motions), which make up an incompressible free shear layer. Some researchers[1–4] have reported that the large-scale vortical motions found within the shear layer are rolled up or spooled laminae resembling a helical spring with small vortices on their periphery. Oster and Wygnanski,[5] using a thermal tagging technique, observed that the vortex core was well mixed and relatively quiescent, whereas large fluctuations were found on their peripheries. Hussain[3] and Fiedler et al.[6] state that the properties in the vortex core are equalized and the internal structure of these large vortices are largely lost by viscous diffusion.

Differing with the preceding view, Brown and Roshko[7] and Dimotakis and Brown,[8] while observing species concentration in a mixing layer, noted a convoluted distribution. Their observations indicate that the surrounding ambient fluid is entrained and entangled within the structure, causing the vortical structure to exhibit large fluctuations in concentration. Dahm and Dimotakis,[9,10] using laser-induced fluorescence, observed that ambient fluid can be found throughout the jet. They further indicate a two-level instantaneous concentration field where these levels differ by a factor of 2 or 3.

This Note, through the presentation of both instantaneous and phase-averaged transverse vorticity measurements, will suggest an inertially active, entangled vorticity distribution within the core of these large-scale structures.

Experimental Study

Vorticity measurements were acquired in a weakly excited incompressible shear layer, generated from a backward facing step, using air as the working fluid. Test section dimensions were $300 \times 50 \times 83$ cm in the x, y, z (streamwise, lateral, and transverse) directions. Signals from an array of hot wires[11] were sampled at 32 kHz. Hot wires were configured as a parallel array (oriented in the y–z plane) with an end flow X-array aligned in the x–y plane. Wires were calibrated over angles ranging from −55 to +55 deg.[12] All experiments were conducted during mechanical excitation of the separating boundary layer. In the present work the freestream velocity U_0 was set to 13 m/s. The mechanical exciter was set to produce an excitation intensity $[\overline{(v')^2}/U_0^2]^{0.5} = 0.00537$ at a Strouhal number of 0.0075, based on U_0 and the momentum thickness of the turbulent boundary layer ($\theta = 6.5$ mm).

A relatively large two-dimensional turbulent boundary layer ($Re_\theta = 5.63 \times 10^3$) and low frequency periodic excitation allowed for the creation of vortical structures approximately 20 cm in width (y direction). Assuming the turbulence is quasi-isotropic, an estimate of Kolmogorov's microscale (η) using $\lambda/\ell \approx \sqrt{15}[Re_\ell]^{-0.5}$ was determined to be 1.23 mm. The ratio of the length scale of the large vortical structures to the dominant characteristic length of the hot-wire array (which was on the order of η) was approximately 160:1.

Results and Discussion

Phase-averaged vorticity ($\langle\omega_Z\rangle$) contours display the educed coherent structure generated by phase averaging 1000 cycles of the excitation mechanism (Fig. 1). In the phase-averaged sense, one may be tempted to view this structure as being composed of sheets of vorticity neatly coiled up, resembling a spool. This can quickly be discounted because of the smearing that takes place when ensemble averaging is performed.[13] A histogram of the $\tilde{\omega}_Z$ (instantaneous vorticity) acquired at a specific x–y location within the core of the vortical motion is shown in Fig. 2. Because of space constraints, a single position within the concentrated vortical core is presented. This histogram was constructed with triangular symbols indicating the sample mean and standard deviation (σ).

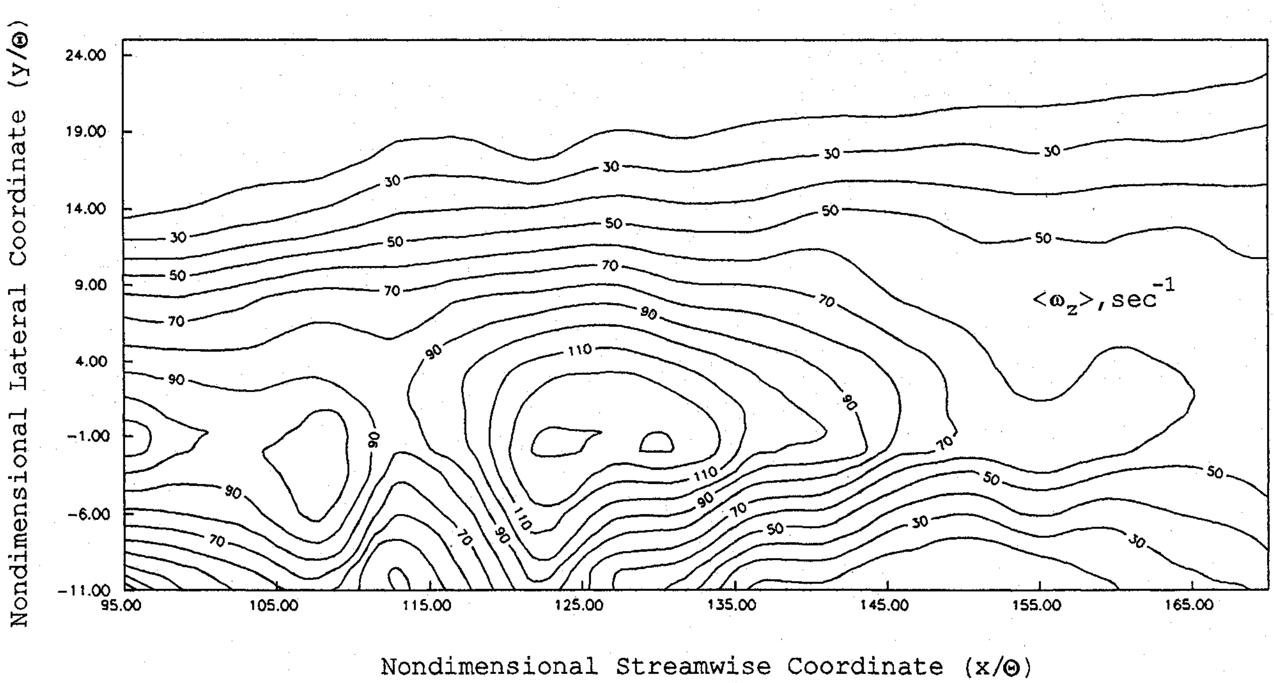

Fig. 1 Phase-averaged transverse vorticity contours.

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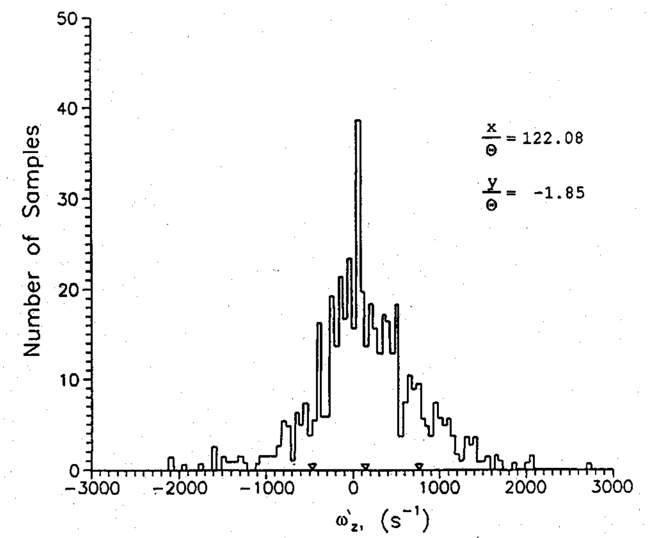

Fig. 2 Instantaneous transverse vorticity histogram within the core of the vortical structure.

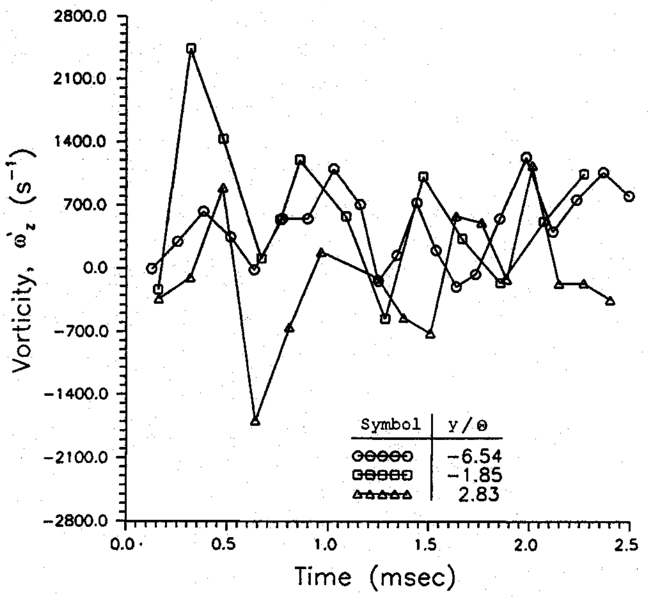

Fig. 3 Transverse vorticity time series within the core at X/Θ = 122.08.

An examination of the histogram indicates that $\acute{\omega}_Z$ levels can consistently fluctuate between four and six times the mean vorticity. Further, if the vorticity distribution is assumed to be approximately Gaussian, and the $\pm 3\sigma$ limits examined, the magnitude of the vorticity within the concentrated core can be observed to exceed the time mean $\langle \omega_Z \rangle$ ($\sim$151 s^{-1}) by as much as 10 times.

Estimates of the small eddy time scales (t_e) based on the measured mean and one σ of $\acute{\omega}_Z$ were determined to be between 2 and 7 ms. The vortex transit time T_t was estimated as 66 ms (or F^{-1}_{Excited}).

Utilizing Kolmogorov's microscale (η), the large-scale vortex Reynolds number ($Re_\ell = u\ell/\nu$), and an approximate turbulence scaling relation $\lambda/\eta \approx 3.873[Re_\ell]^{0.25}$, the Taylor microscale (λ) was approximated to be 26 mm. Incorporating turbulence relations for the time scales, T_λ for the λ eddies is equated to T the time scale of the large vortical motions multiplied by $Re_\ell^{-0.5}$. Relating T to the approximate vortex transit time (T_t), a value of $T_\lambda \sim T_t Re_\ell^{-0.5} =$ 2.24 ms was determined.

Viscous diffusion time scales for both the large vortical motions (T_ν) and the Taylor microscales ($T_{\lambda\nu}$) were determined by R^2/ν (where R is the approximate radius of either the large vortex core $\ell/2$ or the Taylor Microscale, $\lambda/2$): T_ν = 160 s and $T_{\lambda\nu}$ = 11.3 s. Based on a ratio of time scales, the effect of viscous diffusion on the internal structure of the large vortical structure, as well as the Taylor microscale, appears to be over three orders of magnitude weaker than that due to inertia (T_t and T_λ). This reiterates the idea of inertial dominance and its effect on the dynamics of the breakdown process.

Viscous forces based on T_ν and $T_{\lambda\nu}$ appear to be insignificant with respect to the inertial forces even at the smaller scales, the Taylor microscale. Therefore, one can conclude, from the high level of vortical activity within the core, that rapid mixing is accomplished by inertial interactions. Further support for this mechanism is the rate at which core vorticity changes (Fig. 3), indicating the high level of activity and nonequilibrium present. From this figure and the histogram (Fig. 2), large and frequent appearances of negative vorticity emphasize the highly active nature of the large-scale vortex cores.

Conclusions

The observed variations in the vorticity magnitude and the rapid rate of change indicated in Fig. 3 underscore the notion of a highly active and entangled vorticity distribution. Examination of past works, which indicate a high degree of uniformity in the density or temperature within the core of their large-scale motions, also supports this notion. The equilibrium found in these scalar properties is indeed the end effect of this highly active vortical core. Similarly, the reduced vortical activity at the periphery of these large vortical structures confirms the higher degree of nonequilibrium found. Inspection of the various time scales suggests that an inertially dominated interaction is responsible for the rapid mixing of the scalar properties. This appears to occur down to the Taylor microscale, maintaining that the role of viscosity is negligible.

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