Progress toward identification of streamwise vorticity meander in a plane mixing layer

By R. L. LeBoeuf

The main objective of the current project, started in September 1991, is to experimentally investigate streamwise vortical structures in mixing layers. This research program is intended to clarify whether the observed decrease in mean streamwise vorticity in the far-field of mixing layers is due primarily to the "smearing" caused by vortex meander or to diffusion. While preparations for the experiments were underway, the effects of vortex meander on the velocity statistics of a nominally linear array of simulated inviscid line vortices were examined. The two-point transverse velocity cross-correlations were deemed potentially useful for the identification of streamwise vortex meander in a plane mixing layer. Comparisons of these results to forthcoming simultaneous two-point cross-wire measurements in a plane mixing layer should shed some insight into the kinematics of mixing layer streamwise vorticity.

1. Motivation and objectives

An extensive data set consisting of single-point mean and turbulence statistics has been obtained for a two-stream mixing layer generated in the *Mixing Layer Wind Tunnel* (see for example Bell & Mehta 1991). The plane unforced mixing layer was examined in order to quantify the development of streamwise vorticity which previously was identified only through flow visualization studies (e.g. Bernal & Roshko, 1986). The mean streamwise vorticity derived from the mean velocity field shows a continuous decrease with streamwise distance from its nearfield occurrence. It is unclear whether the decrease in mean vorticity is a result of diffusion of the streamwise vorticity or due to meander of concentrated vorticity. Based on comparisons with forced streamwise vortex meander in a boundary layer, Bell & Mehta (1991) argued that the decrease of the mean vorticity in the far-field mixing layer is a result of diffusion.

Townsend (1976) showed that the governing equations for a free-shear flow admit self-preserving solutions for sufficiently high Reynolds numbers. The resulting "self-similar" mean and Reynolds stress profiles become functions of single length and velocity scales. Previous measurements have indicated that the streamwise vorticity persists even in what would normally be considered the "self-similar" region (Bell & Mehta 1991) (where a linear mixing layer growth rate and asymptotic peak Reynolds stresses were achieved). The peak streamwise vorticity and the secondary shear stress ($\overline{uw}$), which was strongly correlated with the streamwise vorticity, were found to exhibit significant levels in this region, (although they decreased with streamwise distance to levels comparable with the noise threshold, Bell & Mehta 1990). It is important for the establishment of the criteria for "self-similarity" to investigate whether the measured decay is due to true diffusion of the streamwise vorticity or is an artifact of meander. In addition, this assessment will have important implications regarding the ability of the layer to enhance mixing and reaction rates in the far-field.

To resolve the questions regarding the persistence of streamwise vorticity in the far-field, it was proposed to perform two-point cross-wire measurements of the velocity field (Bell 1990). The facility and flow conditions of Bell & Mehta (1991) will be used for the current study. A complete description of the facility was given by Bell & Mehta (1989). The existing 3-D traverse used previously to position one cross-wire probe will be used in conjunction with a 2-D traverse which was recently designed and fabricated. While the new hardware and software were being prepared, a preliminary study of two-point "measurements" of a simulated line vortex array was used to determine the usefulness and characteristics of a velocity correlation to be used for the identification of vortex meander.

2. Accomplishments

It was suggested by Bell (1990) that the correlation

$$R_{vv}(Y,Z,r) = \overline{v(Y,Z)v(Y,Z+r)} \tag{1}$$

could be used for the unambiguous identification of streamwise vorticity in the presence of meander. In order to test this hypothesis, $R_{vv}(0,Z,r)$ was computed for simulated ideal line vortices. Twelve vortices with circulation and mean positions matched to the data of Bell & Mehta (1989) for the station 77.6 cm downstream of the splitter plate trailing edge were used for the simulation. The mean vortex centers and circulations found by Bell and Mehta (1989) for this station are listed in Table 1. The measured mean streamwise vorticity distribution is shown in Fig. 1.

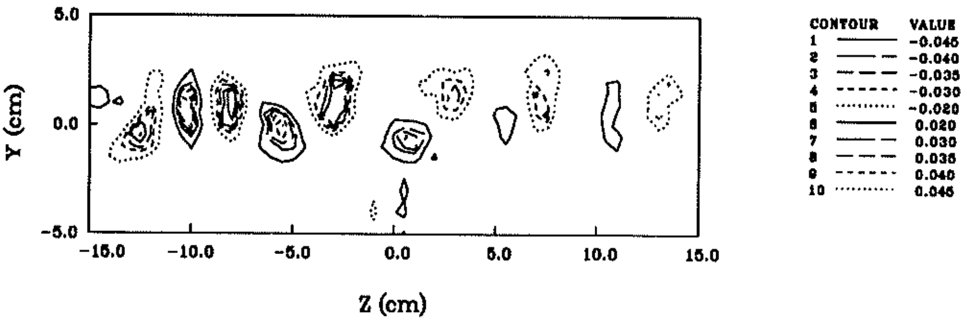

FIGURE 1. Measured mean streamwise vorticity at $X = 77.6$ cm (Bell & Mehta 1989).

Vortex	$\tilde{Y}$ (cm)	$\tilde{Z}$ (cm)	Γ/U_0 (cm)
1	1.0	-15.0	0.056
2	-0.5	-12.5	-0.246
3	0.0	-10.0	0.161
4	1.0	-8.0	-0.176
5	0.0	-5.5	0.166
6	2.0	-3.0	-0.231
7	-0.5	0.5	0.138
8	1.0	3.0	-0.151
9	0.0	5.5	0.069
10	0.5	7.5	-0.159
11	0.5	10.5	0.109
12	2.0	13.5	-0.108

Table 1. Experimental streamwise vortex data at $X = 77.6$ cm (Bell & Mehta 1989).

Vortex "motion" was produced by adjusting the vortex centers to a Gaussian distribution about the mean vortex centers. The transverse velocity component for an array of line vortices is given by:

$$v(Y,Z) = \sum_{j=1}^{12} \frac{\Gamma_j (Z - \tilde{Z}_j)}{2\pi d_j^2} \tag{2}$$

where Γ_j is the circulation of vortex j and the squared distance from the grid point (Y,Z) to the instantaneous vortex center $(\tilde{Y}_j, \tilde{Z}_j)$ is given by

$$d_j^2 = (Y - \tilde{Y}_j)^2 + (Z - \tilde{Z}_j)^2. \tag{3}$$

To avoid singularities at the vortex centers, the velocity was forced to plateau at a value corresponding to an arbitrary minimum distance away from the vortex center of 0.01 cm. The Gaussian distributed deviation of the vortex centers was produced using the IMSL Inc. subroutine RNMVN, which generates pseudo-random numbers from a multivariate normal distribution. Convergence of the correlations was achieved with 8000 points. Various levels of meander were produced by varying the standard deviation of the distribution of the vortex center locations.

The streamwise vortices lie in the braids between the spanwise vortices and are, therefore, inclined and subject to random agitation normal to the mixing layer. This transverse meander is, of course, confined to less than the mixing layer thickness and would be expected to desensitize the proposed measurements to Y positioning. The standard deviation of the transverse meander used for this study was selected based on the nominal mixing layer thickness ($\delta \approx 4$ cm) and the *domain of significant influence* of the vortex ($d_v \approx 1$ cm) for the parameters at the 77.6 cm streamwise location as:

$$\sigma_Y = \frac{1}{2}(\delta - d_v) = 1.5 \text{ cm} \tag{4}$$

Several cases were run with grid spacing of 0.6 cm which corresponds to the minimum probe separation possible in the experiment. The transverse meander was kept fixed at $\sigma_Y = 1.5$ cm as explained above. The spanwise meander was adjusted in 0.5 cm increments to examine the sensitivity of the correlation $R_{vv}(0, Z, r)$ with respect to spanwise meander. The resulting plots of $R_{vv}(0,0,r)$ are included as Fig. 2. The spanwise integral scale is observed to decrease significantly with increasing spanwise meander for constant transverse meander. That is, the spanwise distance over which the transverse velocity component (v) is correlated decreases significantly for large meander. By comparing the correlation results obtained at the near-field stations (where the peak streamwise vorticity is relatively high) with those obtained in the far-field region, it should be possible to establish the role of vortex meander in the far-field.

An additional noteworthy feature of the correlations in Fig. 2 is the off-axis peak of $R_{vv}(0,0,r)$ at $r = 0.5$. This is due to the coincident vortex centered at $Z = 0.5$, very close to the correlation "measurement" axis (i.e. $Y=0$). The introduction of spanwise meander with σ_Z as low as 0.25 cm (not shown in Fig. 2) forces the correlation to peak at $r = 0$ as expected.

3. Future plans

The study of the plane mixing layer will be completed in two parts. The first half of this year will be devoted to the investigation of the mixing layer structure via cross-correlation measurements. The emphasis will be on addressing questions regarding streamwise vortex meander and on establishing details of the initial instability mechanisms and vortex formation. In addition, where possible, an effort will be made to begin comparisons between the proposed measurements and some of the most recent direct numerical simulations.

During the remainder of the program, phase-locked velocity measurements will be performed by acoustically forcing the mixing layer. By establishing a periodic sequence of spanwise vortices, it should be possible to examine the detailed structure of the streamwise vortices. By measuring the scale and spacing of the streamwise vorticity in the braid region of the mixing layer, more direct comparisons of the wind tunnel measurements can be made with the direct numerical simulations of the same flow (Rogers, M. M. & Moser, R. D. private communication). In particular, initial conditions (streamwise vortex strength and distribution) will be measured in detail so that they may be used as input to numerical simulations.

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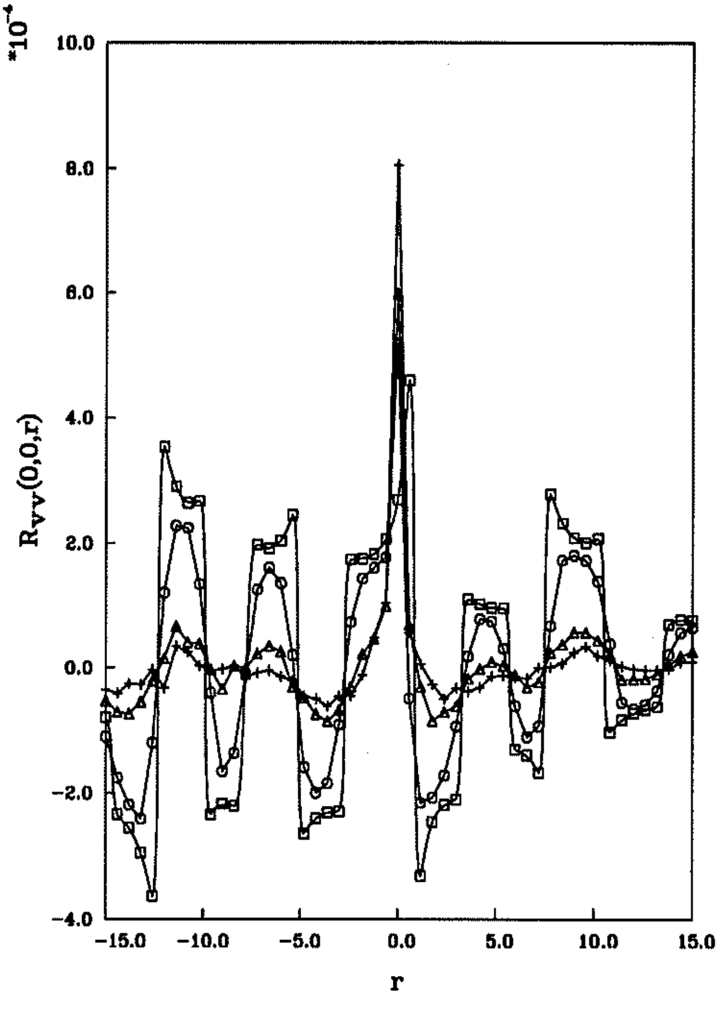

FIGURE 2. Cross-correlation of simulated line vortices for $\sigma_Y = 3/2$. □ , $\sigma_Z = 0$; ○ , $\sigma_Z = 1/2$; △ , $\sigma_Z = 1$; + , $\sigma_Z = 3/2$.

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