Extraction and Dynamical Modeling of Large-Scale Coherent Structure in the Planar Turbulent Jet

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The large-scale coherent structure in the turbulent planar jet similarity region is experimentally investigated by application of the proper orthogonal decomposition (POD) and the underlying dynamics modeled. The POD spatial eigenfunctions for each of the three velocity components are extracted by means of twin cross-stream rakes of x-wire probes positioned with different spanwise separations. POD eigenvalue convergence is demonstrated to be rapid. When properly scaled by global flow field variables the eigenfunctions and eigenvalues are shown to exhibit self-similarity.

The large-scale structure is reconstructed in physical space by projection of measured $u$, $v$, and $w$-component POD eigenmodes onto instantaneous flow field realizations. The projection is performed by means of a continuous wavelet transform-based technique. The instantaneous flow field realizations are obtained by a triple x-wire rake arrangement. This arrangement allows the unambiguous extraction of the planar component of the jet structure as well as the most energetic nonplanar part. Results indicate that a dominant planar component of the large-scale structure in the planar jet consists of two lines of large-scale spanwise vortices arranged approximately asymmetrically with respect to the jet centerline. This planar component of the structure resembles the classic Karman vortex street. There is a strong interaction between structures on opposite sides of the jet in the form of lateral streaming motions that extend well across the flow. Figure 1(a) presents a sample of both the velocity vector field and instantaneous streamlines associated with the planar component of the jet coherent structure obtained by superimposing the mean flow and the first three planar POD modes. The velocity data is presented in the frame of reference moving downstream with the constant convective speed $U_c$. Taylor’s hypothesis is invoked in order to convert time into a pseudo-spatial streamwise coordinate $x = -U_c t$. All spatial coordinates have been non-dimensionalized by the local mean velocity half-width $b$.

Investigation of the nonplanar modes shows that their effect is to tilt and bend the spanwise vortex tubes. The bending occurs primarily in the streamwise direction. The degree to which the spanwise vortices are distorted varies greatly; in some cases they are nearly streamwise oriented and in others only slight distortion of a spanwise vortex is noted. A few examples are shown in Figure 1(b). This figure shows instantaneous streamline surfaces which wrap around a spanwise vortical structure thereby revealing the flow pattern near the core. Two projections are also shown in gray to facilitate visualizing these 3-D surfaces. Although only a single nonplanar mode was examined, in reality a continuous spectrum of nonplanar modes $k_z b / 2\pi < 1$ will distort the spanwise vortices. The result will be similar in overall topology to that presented in Figure 1(b) but will involve finer scale convolutions of the primary vortex tube.
Figure 1: a) Reconstructed flow field for planar coherent structure and b) several examples of the reconstructed 3-D flow field around non-planar structures.

The rapid energy convergence of the POD modes leads to the possibility of building a realistic local low-dimensional model of the planar jet based on the interaction of the large-scale structures. Due to the dominance of the first planar component over the nonplanar components, only the first two planar POD modes are used in the model. In the streamwise direction each POD mode is approximated as a discrete finite sum of the Fourier modes. The velocity field is considered to be a sum of the time-independent mean flow and the dominant planar modes. After the Galerkin projection of the POD-based velocity expansion onto the Navier-Stokes equations, the system of ODE’s is obtained and numerically investigated. The influence of the unresolved modes is treated as a simple viscous dissipation acting on the resolved modes. The number of resolved modes and the amount of dissipation due to unresolved scales is varied and it’s impact on the model is discussed. Results of the modeling are compared with the experimental data and found to have a very good agreement. It is shown that the model still predicts quantitatively the essential local dynamical behavior of the planar jet with as low as 20 equations. The extension of the model to a range Reynolds numbers and the possibility of obtaining global dynamics of the jet are discussed.