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Short Paper

The Visualization of Three-Dimensional Vortex Structures in a Mixing Layer

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1. Introduction

A plane mixing layer consisting of two parallel streams with different velocities is a classical field for the study of turbulence in free shear layers (Ho and Huerre, 1984). This flow has been extensively studied for the past few decades owing to its relatively simple geometry which allows its theoretical analysis (Ashurst and Meiburg, 1988), numerical simulation (Rogers and Moser, 1992; Moser and Rogers, 1993), as well as experimental investigation (Lasheras and Choi, 1988). The theoretical analysis has indicated that the streamwise vorticity introduced into the shear layer always stretches the braids between consecutive spanwise vortices under the positive strain and then propagates into their cores. The counter-rotating 'rib' vortices were also found in most numerical simulations. The wavelength of the three-dimensional instability was found to be about two-thirds of the wavelength of the two-dimensional instability. The experimental investigations on a chemically reacting mixing layer (Lasheras et al., 1986) ascertained that the coherent streamwise structures were the result of unstable response to three-dimensional upstream perturbations. The transition to three-dimensionality depends on the magnitude and location of the upstream disturbances. It has been shown in above studies that the plane mixing layer contains rich information regarding the evolution and interactions of turbulent coherent structures, however, the fundamental of turbulence and the evolution of the vortex structures were not being thoroughly understood, and the visualization of the 3-D vortex structures was also seldom reported. It is of great significance to understand the fundamental of coherent vortex structures for the engineering application in many producing processes.

With advancements in computer science and technology, direct numerical simulation (DNS) has become a very powerful tool to solve three-dimensional, time-dependent Navier-Stokes equations. In this work, Spectral method was used to simulate the turbulent flows as they converge quickly and produce very high spatial resolution. The motivation of this study is to enhance the understanding of the physical phenomena in the turbulent coherent structures by the visualization of the process of roll-up and paring.

2. Formulation and Numerical Procedure

The non-dimensional continuity and momentum equations for an incompressible flow with no body force are:

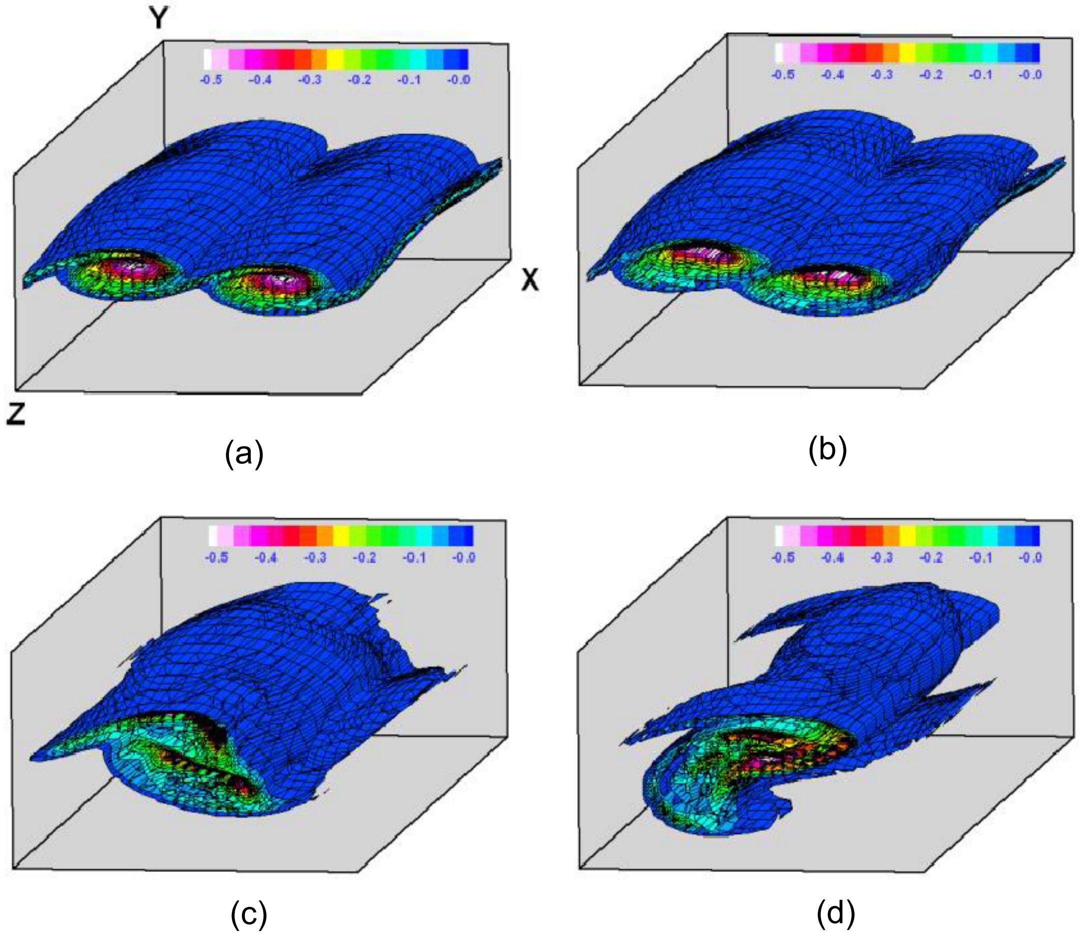
$$\nabla \bullet \boldsymbol{U} = 0 \tag{1}$$

$$\frac{\partial \boldsymbol{U}}{\partial t} = \boldsymbol{F} - \nabla \Pi + \frac{1}{\boldsymbol{Re}} \nabla^2 \boldsymbol{U} \tag{2}$$

where $\boldsymbol{F} = \boldsymbol{U} \times \boldsymbol{\omega}$,with the vorticity $\omega = \nabla \times \boldsymbol{U}$. Π is the total pressure. Reynolds number $\boldsymbol{Re} = U_0 \theta_0 / \nu$, in which $U_0 = (U_1 - U_2)$ and θ_0 (the double initial momentum thickness) are taken as characteristic velocity and length, respectively. A pseudo-spectral method was employed to solve the governing equations. Along the homogeneous directions (*X*, *Z*), spatial derivatives can be expressed by Fourier expansions due to the periodic boundary conditions. In the transverse direction (*Y*), where the perturbation attenuates rapidly, the solutions can also be represented by the same expansion by employing mirror image extending.

3. Visualization of 3-D Vortex Structures

Figure 1 shows the evolution of the three-dimensional spanwise vorticity with time, it can be seen that the well-developed Kelvin-Helmholtz rollers come together, co-rotate and eventually amalgamate to form a new bigger roller, which was caused by the initial perturbations on the subharmonic unstable wave number. As the core of the original spanwise rollers merge, spiral arms of weaker spanwise vortex are ejected away from the paired eddy. The tips of these spiral arms develop a characteristic hook shape and are eventually drawn back into the surviving braid regions between the paired eddy and its periodic images.



(a) (b)

(c) (d)

Fig. 1. Three-dimensional spanwise vortex structures with time, (a) T = 35; (b) T = 45; (c) T = 65; (d) T = 85.

Figure 2 shows the three-dimensional contours of streamwise vorticity. The solid lines represent positive values of the vorticity and the dashed lines represent negative values. The streamwise ‘rib’ vortices were seen to form first on the braids between consecutive spanwise vortices and then propagate into their cores (T = 45) which agrees well what was observed experimentally by Lasheras and Choi (1986). Besides the ‘ribs’, the elliptic vortices, which can be clearly observed at T = 35 (dashed lines, green color), are also notable vortices. With increasing time, the two elliptic vortices come together, extruding the interbedded ‘rib’ vortex and shortening it (T = 65), the streamwise ‘ribs’ outside the elliptic vortices continue stretching and gradually come up to approximately parallel vortex tubes structures (T = 85). Meanwhile, some small ‘ribs’ in core regions induced by larger ones are regrouping and then form more complicated structures.

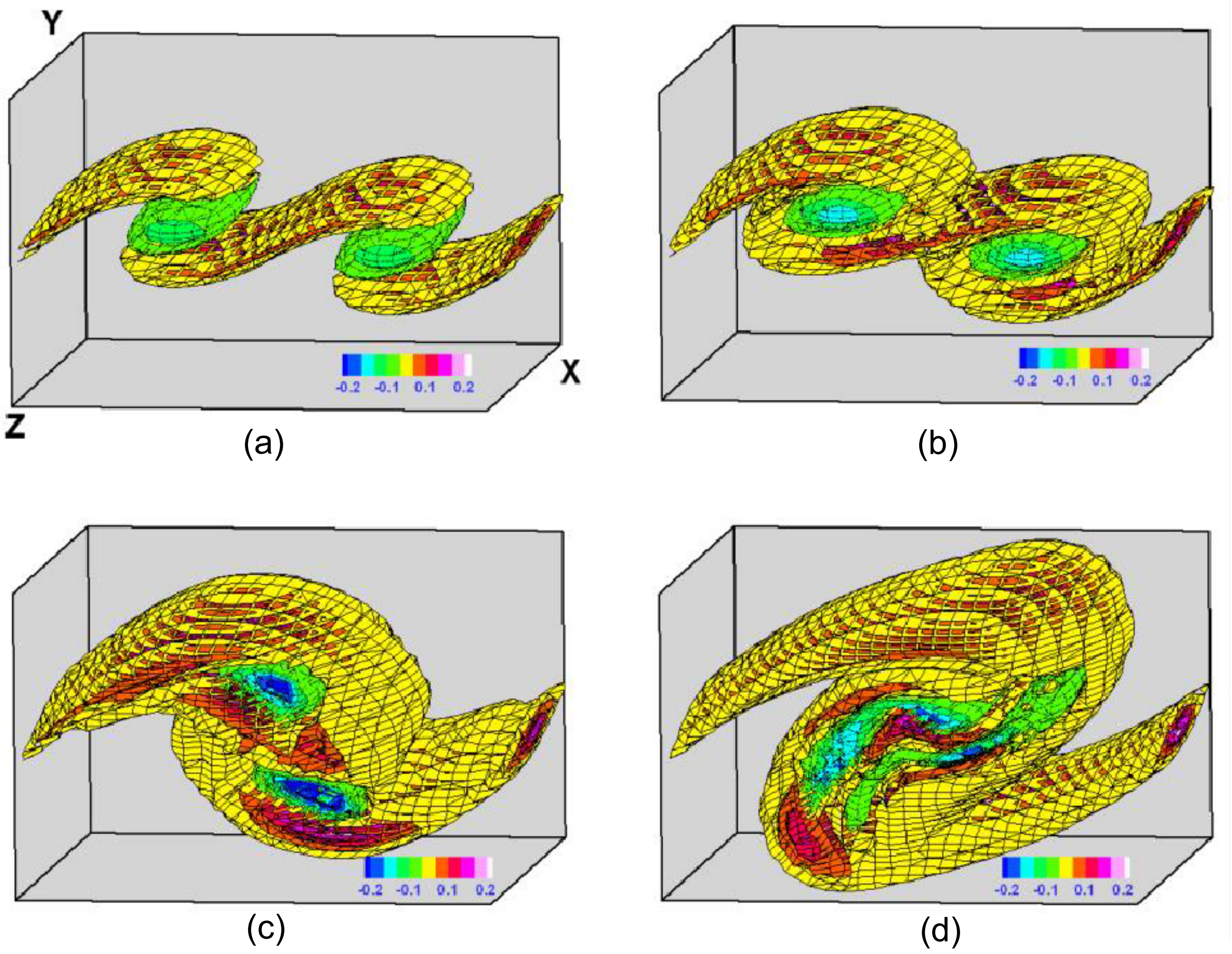


Fig. 2. Three-dimensional profiles of steamwise vorticity with time, (a) T = 35; (b) T = 45; (c) T = 65; (d) T = 85.

Acknowledgements

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