J Vis (2010) 13:273–274
DOI 10.1007/s12650-010-0046-x

PORTFOLIO PAPER

Xiaotian Shi · Jun Chen · Zhensu She

Visualization of compressibility effects on large-scale structures in compressible mixing layers

Received: 29 March 2010 / Revised: 23 May 2010 / Accepted: 31 May 2010 / Published online: 4 July 2010

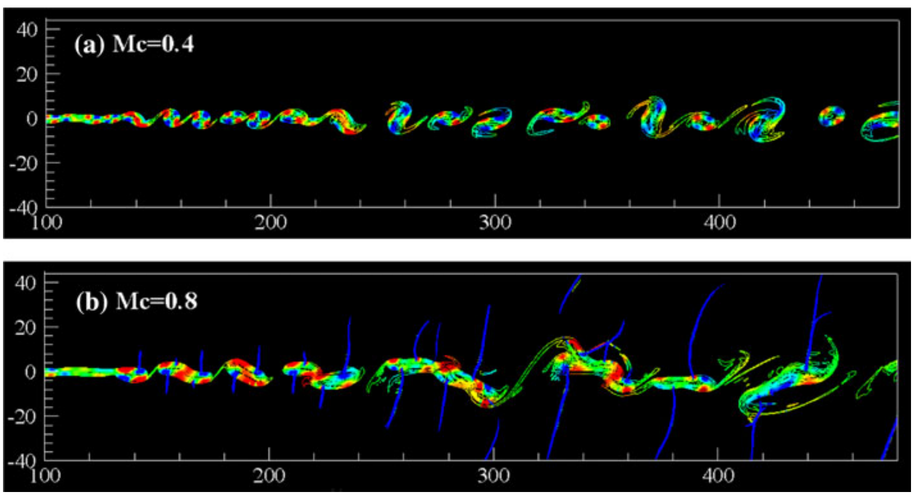

Fig. 1 Vorticity, ω, velocity divergence, $\nabla \cdot \vec{u}$, and the magnitude of pressure gradient, $|\nabla p|$, from DNS of 2-D compressible mixing layers. The mixing layer convects from *left to right*. The higher speed stream is at the upper portion of the flow field, and the lower speed stream is at the lower side of the flow field. ω is plotted by contour, the *colors* of which represent velocity divergence. Pressure waves are identified by $|\nabla p|$ with *blue contours*. **a** $M_c = 0.4$. The contour levels for ω range from -1.24 to 0.01 with 30 levels. The color levels for $\nabla \cdot \vec{u}$ range from -0.001 to 0.001. **b** $M_c = 0.8$. The contour levels of ω range from -1.24 to 0.01 with 30 levels. The color levels for $\nabla \cdot \vec{u}$ range from -0.005 to 0.005. The boundary for $|\nabla p|$ is determined by 0.1

Vorticity, ω, velocity divergence, $\nabla \cdot \vec{u}$, and the magnitude of pressure gradient, $|\nabla p|$ are visualized in a same flow domain, to reveal large-scale, dilatation and shocklet structures in a compressible mixing layer from direct numerical simulation results. We simulated 2-dimensional (2-D) and 3-dimensional (3-D) compressible mixing layers with a third-order Discontinuous Galerkin method (Cockburn and Shu 1998) and a third order explicit Runge–Kutta time advancement scheme. The grid numbers are 5.04×10^5 for 2-D cases, and 4.6×10^6 for 3-D case. The resulting variants are normalized with the density ρ, the speed of sound a and ρa^2 of the free streams. A perturbation signal with a broadband spectrum and a peak at the most unstable frequency in incompressible case, in conjunction with a hyperbolic tangent mean velocity profile are imposed

X. Shi · J. Chen (✉) · Z. She
State Key Laboratory for Turbulence and Complex Systems, College of Engineering, Peking University, Beijing 100871, China
E-mail: jun@pku.edu.cn

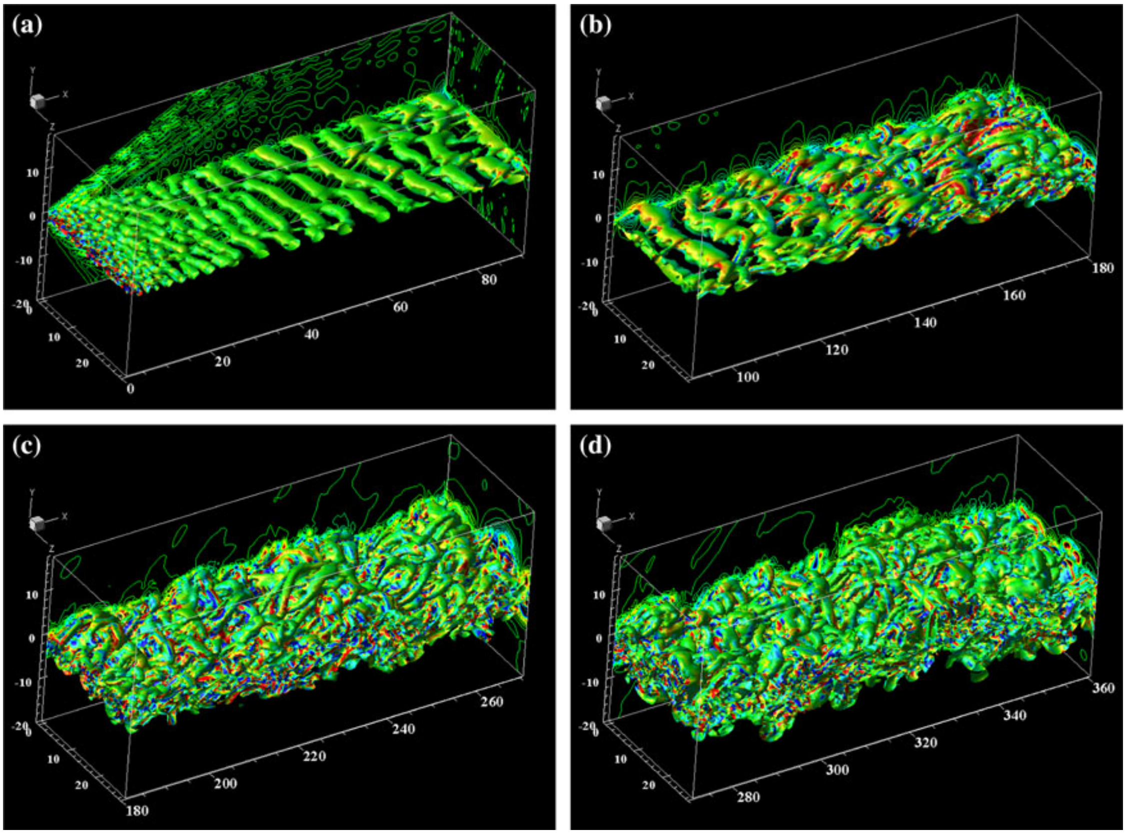

Fig. 2 Large-scale vortices in a 3-D spatial developing compressible mixing layers at $M_c = 0.4$ from upstream to downstream, shown by the iso-surface of Q_2 ($Q_2 = 0.001$) and colored with the divergence of velocity ranging from -0.015 to 0.015 with 30 contour levels

as inlet condition. Characteristic nonreflecting boundary condition is used at both longitudinal boundaries and outlet boundary. Figure 1 shows the large-scale structures, named *coherent vortices* or *Brown–Roshko vortices* at $M_c = 0.4$ and 0.8. To visualize the compressibility effects on large-scale structures in high-speed compressible mixing layers, we use a hybrid visualization method to visualize large-scale structures with (a) vorticity or Q_2-method (Hunt et al. 1988) to identify vorticity structures; (b) contour of the amplitude of pressure gradient to mark pressure waves and *shocklets*, and (c) the color of vorticity contours to represent the divergence of velocity. Figure 2 shows the visualization of 3-D $M_c = 0.4$ case. For 2-D cases, the coherent vortices are regular and the fluid expands in one direction while is compressed in another direction, pressure waves radiate from the center of the mixing layer to the free streams. As M_c increases the pressure waves shrink to narrow bands and develop into shocklets at the downstream regions, marked in deep blue color in Fig. 1b. For the 3-D cases, the second instability in spanwise accounts for riblets, and the forests of lambda structures emerge, and make the flow field fully turbulent. The multi-variant visualization of a compressible flow region with vorticity, velocity divergence and pressure gradient introduced here is efficient to reveal complex structures under compressibility effects in mixing layers, and could also be applied to other compressible flows, such as compressible boundary layers.

Acknowledgments This work is supported by the Chinese National Natural Science Foundation grants 90716008, 10572004, MOST 973 project 2009CB724100 and CSSA. Thanks to the PC Clusters of the Peking University.

References

Cockburn B, Shu C-W (1998) The Runge–Kutta Discontinuous Galerkin method for conservation laws V: multidimensional systems. J Comput Phys 141-2:199–224

Hunt JCR, Wray AA, Moin P (1988) Center for turbulence research report CTR-S88, pp 193–208