COMPRESSIBILITY EFFECTS ON SPATIALLY DEVELOPING PLANE FREE SHEAR LAYER

Allocation: Innovation and Exploration/190 Knh
PI: Farzad Mashayek[1]
Co-PIs: Jonathan Komperda[1], Dongru Li[1], Ahmad Peyvan[1]

[1]University of Illinois at Chicago

BW

EXECUTIVE SUMMARY

Compressible turbulent free shear flows have a wide variety of applications in modern technology and commonly occur in engineering systems such as gas turbines, scramjet engines, rocket exhausts, and the like. However, a fundamental understanding of the physics of such flows is limited by a lack of detailed information about the turbulent transition process and the turbulent quantities under the influence of compressibility. This work is the first computational effort to investigate the compressibility effects on the transition to turbulence and the turbulent energy exchange mechanisms in a three-dimensional, spatially developing turbulent plane free shear layer, via data produced by direct numerical simulation (DNS). The DNS was performed using a high-order discontinuous spectral element method for different convective Mach numbers with a naturally developing inflow condition. The location of the transition zone was predicted by the analyses of vorticities and the turbulent viscous dissipation rate. The energy exchange was examined via the analyses of the budget terms of turbulent kinetic, mean kinetic, and mean internal energy transport equations.

RESEARCH CHALLENGE

DNS can generate all the information in a turbulent flow, which is impossible to accomplish experimentally. However, most of the DNS were performed on a temporally developing turbulent flow owing to its much lower computational cost compared to its counterpart—spatially developing flow. For the DNS of a highly compressible free shear layer (FSL), the spatially developing approach is the closest realization of a transition experiment. Therefore, the research team developed a computational model for a three-dimensional (3D), spatially developing turbulent plane FSL, with a naturally developing inflow condition, using DNS of the compressible full Navier–Stokes equations. This computational model employs a highly accurate numerical method, the high-order discontinuous spectral element method (DSEM) [1–3], to deal with the complicated issues arising in a highly compressible turbulent flow in an open computational domain for an FSL.

METHODS & CODES

The research team performed DNS on Blue Waters using a high-order DSEM [1–3]. The DSEM used hexahedral nonoverlapping elements in an unstructured grid. A high-order local basis function approximated the solution variables in each element [1,2]. Such features make the DSEM powerful in terms of handling complex geometries, local mesh refinement, efficient parallelization, and easy boundary condition implementation. Such discretization also enabled the team to interpolate the solution to a new local basis function with a different polynomial order within each element in order to change the grid resolution during simulation. The method introduces negligible diffusion and dispersion errors and is spectrally convergent for smooth solutions [1,2]. In the current work, the grid consists of 1,368,260 elements with a polynomial order of p = 5, resulting in a total of 295,544,160 solution points. The team's scaling study indicated that using 2,048 cores is ideal for performing the simulations, considering that the efficiency is relatively high (82%) on Blue Waters.

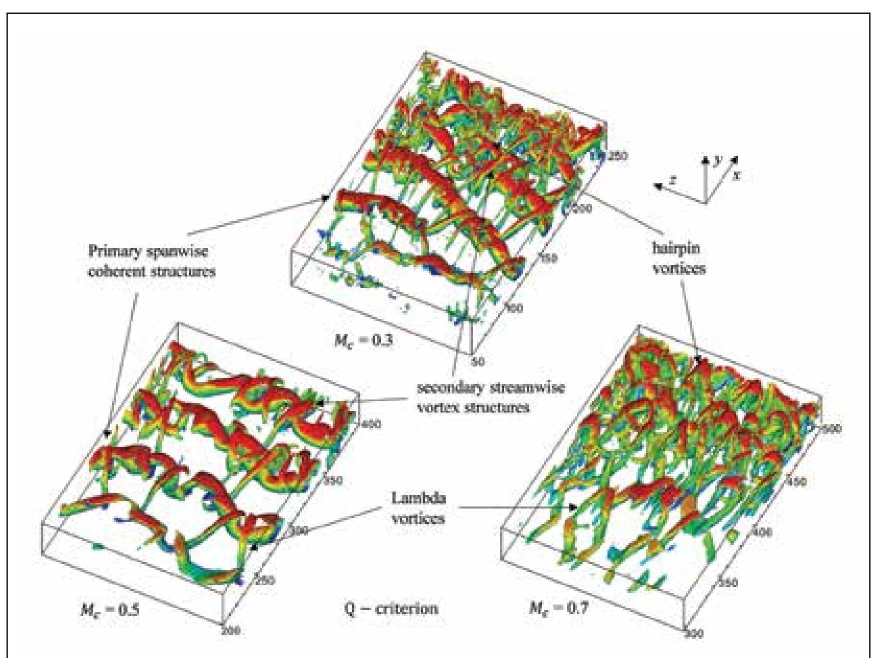

Figure 1: Iso-surface of the second invariant of velocity gradient tensor colored by streamwise velocity with convective Mach numbers of 0.3, 0.5, and 0.7. All terms are normalized by ΔU, which is the difference between the high- and low-speed streams.

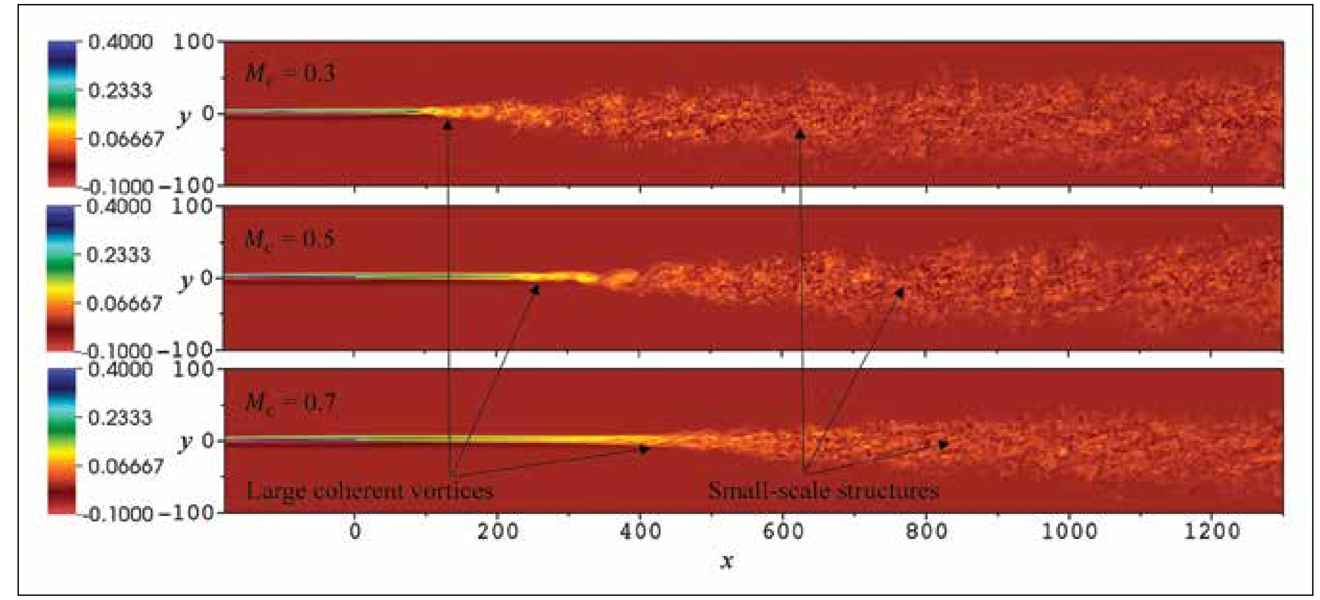

Figure 2: Spanwise vorticity contours for the cases with convective Mach numbers of 0.3, 0.5, and 0.7. The computed vorticity is normalized by ΔU, which is the difference between the high- and low-speed streams.

RESULTS & IMPACT

This work presents the first DNS results for a spatially developing, 3D compressible turbulent FSL with a naturally developing inflow condition for different convective Mach numbers. It shows a 3D representation of the instantaneous turbulent structures via iso-surface of the second invariant of velocity gradient tensor for convective Mach numbers of 0.3, 0.5, and 0.7 (Fig. 1). Further, it demonstrates the vortex stretching mechanism in the spanwise direction, such as the formation of secondary streamwise vortices and the breakdown of primary spanwise vortices, which are responsible for the onset of turbulence transition. Also, the contours of the instantaneous spanwise vorticity (Fig. 2) indicate the location of the turbulence transition region under the influence of compressibility for each case. The spiral-type roll-ups can only be observed in the flow with the highest convective Mach number, 0.7. The instantaneous variables and their statistics were used to investigate the compressibility effects on turbulence transition and turbulent energy exchange and to calibrate turbulence models.

This work conducts the DNS of an FSL to generate detailed data for all flow field variables in both the transition and self-similar turbulent regions for different convective Mach numbers. It identifies the location of the turbulence transition zone under the influence of compressibility. It determines the energy exchange mechanisms responsible for energy redistribution among turbulent kinetic energy, mean kinetic energy, and mean internal energy and examines the influence of compressibility on such mechanisms. It provides calibrations for turbulent models.

WHY BLUE WATERS

To resolve all relevant scales of turbulent structures, the grid used in this work consisted of roughly 0.3 billion solution points. Also, the generation of full statistics for the cases required the computation and storage of 47 variables for fluctuations, nine for averages, five for instantaneous variables, and three for coordinates. The storage of these variables was necessary both on disk as well as in memory at runtime, which exceeds the available storage space and memory available per core on many supercomputers. Thus, this combination of computation and data storage is well suited for a leading-edge petascale high-performance computing system such as Blue Waters.

PUBLICATIONS & DATA SETS

D. Li, J. Komperda, Z. Ghiasi, A. Peyvan, and F. Mashayek, "Compressibility effects on the transition to turbulence in a spatially developing plane free shear layer," *Theor. Comput. Fluid Dyn.*, vol. 33, no. 3, 2019, doi: 10.1007/s00162-019-00507-w.