Numerical Study of Variable Density Turbulence Interaction with a Normal Shock Wave

Y. Tian, tianyife@egr.msu.edu
F. A. Jaberi, jaberi@egr.msu.edu
Z. Li, Zhaorui.Li@tamucc.edu
D. Livescu, livescu@lanl.gov

Accurate numerical simulations of shock-turbulence interaction (STI) are conducted with a hybrid monotonicity-preserving-compact-finite-difference scheme for a detailed study of STI in variable density flows [2]. Theoretical and numerical assessments of data confirm that all turbulence scales as well as the STI are well captured by the computational method. Linear interaction approximation (LIA) convergence tests conducted with the shock-capturing simulations exhibit a similar trend of converging to LIA predictions to shock-resolving direct numerical simulations (DNS). The turbulence amplification by the normal shock wave is much higher and the reduction in turbulence length scales is more significant when strong density variations exist. Turbulent mixing enhancement by the shock is also increased and stronger mixing asymmetry in the post-shock region is observed when there is significant density variation. The turbulence structure is strongly modified by the shock wave, with a differential distribution of turbulent statistics in regions with different densities. The dominant mechanisms behind the STI are identified by analysing the transport equations for the Reynolds stresses, vorticity, normalized mass flux and density specific volume covariance.

Background and Motivation

The interaction between a normal shock wave and isotropic turbulence is an important fundamental problem which has been extensively studied. An understanding of the physics behind this problem is beneficial to many applications such as hypersonic combustion, inertial confinement fusion and astrophysics. However, the existence of a wide range of length/time scales and other complicating effects in flows involving both turbulence and shock waves have posed serious challenges in the study of these flows. For the study of the canonical STI problem, both theoretical and numerical investigations have achieved some success in revealing the underlying physics.

The current work focuses on the numerical study of multi-fluid STI, which is important to a range of compressible flows with strong density variations. Our preliminary results have shown general characteristics of multi-fluid STI [3].The goal of the current study was to develop a better understanding of the density effects on the shock-turbulence interaction and scalar mixing.

Computational Setup and Numerical Accuracy

The conservative form of the dimensionless compressible Navier-Stokes equations for continuity, momentum, energy, and scalar are solved numerically together with the perfect gas law using a high-order hybrid numerical method. The inviscid fluxes are computed by the fifth-order MP scheme. The viscous fluxes are calculated by the sixth-order compact scheme. The 3rd-order Runge-Kutta scheme is used for time advancement. The physical domain for the simulations considered is a box that has a dimension of $(4\pi, 2\pi, 2\pi)$ as shown in figure 1. Pre-generated multi-fluid isotropic turbulence with $M_t = 0.1$, $Re_\lambda = 45$ and $A_t = 0.28$ is convected through the inflow. The normal shock is located in the middle of the domain and has a Mach number of 2.0.

Convergence tests are conducted to establish the accuracy of numerical results using different meshes with a wide range of grid sizes. The computed statistics are found to be independent of the grid when the turbulence after the shock is well resolved and the scale separation between the numerical shock thickness and the turbulent scales is adequate, as suggested in [1]. LIA convergence tests are then conducted to show that

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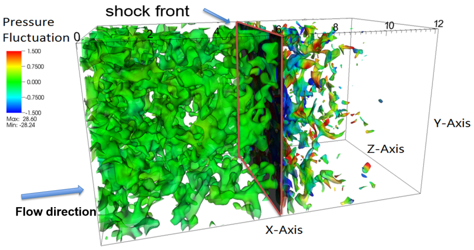


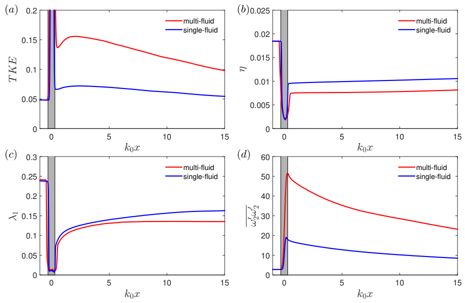
Turbulent structures, identified by the 3D isosurface of the heavy fluid mole fraction, colored by the local pressure fluctuations in a Mach 2 isotropic turbulence.

shock-capturing simulations exhibit similar converging trends to LIA predictions as in shock-resolving DNS [1]. These results establish shock-capturing simulation as an effective tool in studying STI.

Main Results and Conclusions

The modification of turbulence statistics by the normal shock is shown to be different from those of the single-fluid case, with an increased amplification of turbulence variables (like turbulent kinetic energy and vorticity variance) and a more significant reduction in turbulence length scales (see figure 2). Turbulent mixing enhancement by the shock is also more significant in the multi-fluid cases. Redistribution of turbulence statistics across the shock wave is another important feature of multi-fluid STI, as reflected in the changes in the conditional expectations. It is found that the TKE has a preferential distribution in the pure-fluid regions after the shock wave, while the vorticity amplification is strongest in the mixed-fluid areas. This difference is attributed to the different roles that density plays for these quantities.

The dominating mechanisms in the development of post-shock turbulence are identified by analyzing the transport equations for the interested turbulent statistics. The Reynolds stress are mainly controlled by the pressure-strain and velocity-pressure correlation, which exhibits shorter but more intense transients when there are significant density variations. Turbulence stretching plays an important role in the post-shock development of vorticity variance. A faster return to isotropic turbulent state for the multi-fluid case is observed by examining the normalized turbulence stretching. The budgets of modeling quantities in multi-fluid turbulence mixing are also studied and are provided as accurate data for testing the mixing models.



Plots of (a) turbulent kinetic energy, (b) Kolmogorov length scale, (c) Taylor micro scale and (d) transverse vorticity variance for multi-fluid (red) and single-fluid (blue) simulations.

Acknowledgements

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