STATISTICS OF THE SUBGRID SCALES AFTER THE SHOCK-TURBULENCE INTERACTION

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Abstract The interaction of a shock wave with isotropic turbulence (IT) represents a basic problem for studying some of the phenomena associated with high speed flows, such as hypersonic flight, supersonic combustion and Inertial Confinement Fusion (ICF). In general, in practical applications, the shock width is much smaller than the turbulence scales and the upstream turbulent Mach number is modest. In this case, recent high resolution shock-resolved Direct Numerical Simulations (DNS) (Ryu and Livescu, J. Fluid Mech., 756, R1, 2014) show that the interaction can be described by the Linear Interaction Approximation (LIA). By using LIA to alleviate the need to solve the shock, DNS post-shock data can be generated at much higher Reynolds numbers than previously possible. Here, such results with Taylor Reynolds number ≈ 180 are used to investigate the properties of the subgrid scales (SGS). In particular, it is shown that the shock interaction decreases the asymmetry of the SGS dissipation PDF as the shock Mach number increases, with a significant enhancement in size of the regions and magnitude of backscatter.

The interaction of shock waves with turbulence is an important aspect in many types of flows, from hypersonic flight, to supersonic combustion, to astrophysics and ICF. In general, the shock width is much smaller than the turbulence scales, even at low shock Mach numbers, M_s, and it becomes comparable to the molecular mean free path at high M_s values. When there is a large scale separation between the shock and turbulence, viscous effects become negligible during the interaction. If, in addition, the turbulent Mach number, M_t, of the upstream turbulence is small, the nonlinear effects can also be neglected during the interaction. In this case, the interaction can be treated analytically using the linearized Euler equations and Rankine-Hugoniot jump conditions. This is known as the Linear Interaction Approximation (LIA) [3]. However, due to the high cost of simulations for the parameter space close to practical applications and difficulties with accurate measurements close to the shock, previous studies studies have demonstrated only limited agreement with LIA. Recently, Ryu and Livescu [6], using high resolution fully resolved DNS extensively covering the parameter range, have shown that the DNS results converge to the LIA solutions as the ratio δ/η, where δ is the shock width and η is the Kolmogorov microscale of the upstream turbulence, becomes small. The results reconcile a long time open question about the role of the LIA theory and establish LIA as a reliable prediction tool for low M_t turbulence-shock interaction problems. Furthermore, when there is a large separation in scale between the shock and the turbulence, the exact shock profile is no longer important for the interaction, so that LIA can be used to predict arbitrarily high M_s interaction problems, when the Navier-Stokes equations are no longer valid and fully resolved DNS are not feasible.
The shock-turbulence interaction has been traditionally studied in an open-ended domain, with the turbulence fed through the inlet plane encountering a stationary shock at some distance from the inlet. This approach is very expensive even when a shock capturing scheme is used and limited to low Reynolds numbers. However, the range of the achievable Re values can be significantly increased if, instead, one uses the LIA theory to generate the post-shock fields. In order to be able to generate full 3-D fields, Refs. [6, 7, 2] have extended the classical LIA formulas, which traditionally have been used to calculate second order moments only. Using this procedure, Refs. [6, 7, 2] have shown profound changes in the structure of post-shock turbulence, with significant potential implications on turbulence modeling.
While fully resolved simulations of turbulence interacting with shocks are prohibitively expensive at practical Re values, Large Eddy Simulations (LES) approaches have to contend with contradictory requirements for the numerical algorithms to simultaneously capture both the turbulence and the shocks. Thus, turbulence simulations require the minimization of numerical dissipation for small scale representation, while the shocks require increased local dissipation to regularize the algorithm [1]. Explicit subgrid models also need to account for the presence of the shock. Yet, available high Re data necessary to investigate the SGS properties and test the LES models are scarce. This study aims at using the novel procedure proposed by Ryu and Livescu [6] to generate high Re post-shock data and study the changes in the SGS properties following the shock interaction.

RESULTS

High Re post-shock DNS data are generated by first performing triply periodic forced compressible isotropic turbulence (IT) simulations using the linear forcing method [5]. This forcing method has the advantage of specifying the Kolmogorov micro scale and ratio of dilatational to solenoidal kinetic energies, χ, at the outset. Here, we present results from simulations with $Re_\lambda \approx 180$, $\chi = 0.01$ (quasi-vortical turbulence) and $M_t = 0.05$. The resulting turbulence fields are passed through the generalized LIA formulas [6, 7, 2] to obtain the post-shock turbulence data. In order to examine the properties of the subgrid scales, the post-shock data is filtered using a Gaussian filter.
The usual picture of an energy cascade typically holds in a statistically-averaged sense, it does not always describe the local behavior of a turbulent flow. The turbulent dissipation is actually the difference between two energy fluxes, a "forwardscatter", corresponding to the classical energy cascade, and the "backscatter", a reversal of this process in which

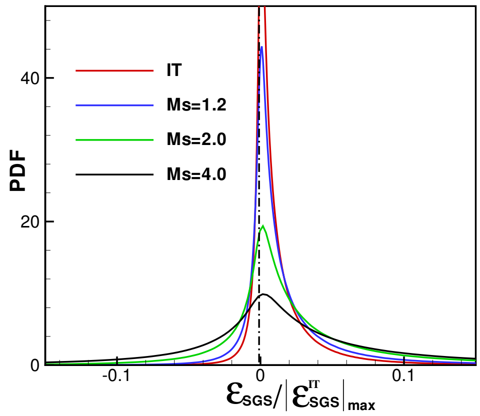

Figure 1. PDF of SGS dissipation for IT and post-shock turbulence at several shock Mach numbers. Negative values are associated with backscatter. The IT PDF data corresponds to the whole 3-D domain, while post-shock data corresponds to the plane of maximum amplification of the streamwise Reynolds stress.

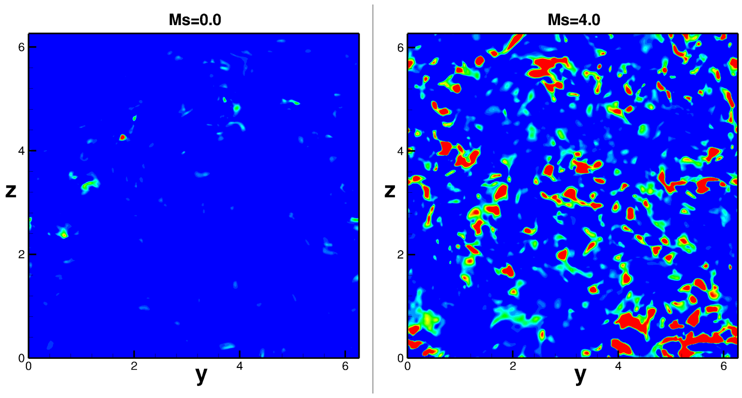

Figure 2. Distribution and magnitude of backscatter (negative values of SGS dissipation) in a) IT and b) in the transverse plane corresponding to the maximum amplification of the streamwise Reynolds stress after a $M_s = 4$ shock.

energy is transferred from the small scales back to the large scales. In LES approaches, the SGS backscatter acts as a source term in the kinetic energy equation and poses significant difficulties in maintaing stable computations [4]. Many of the simple SGS models do not account for backscatter and properly describing this phenomenon is an active area of research [4].

Figure 1 compares the Probability Density Function (PDF) of the SGS dissipation between IT and post-shock data at several M_s values. In IT, the regions with backscatter and the magnitude of the negative SGS dissipation are limited as the PDF is strongly skewed towards positive values. However, post-shock turbulence exhibits a more symmetrical PDF and a strong increase in the variance at higher M_s values. Indeed, figure 2 shows that the backscatter activity increases considerably in post-shock turbulence, with important consequences on SGS modeling of such flows.

References

[1] E. Johnsen, J. Larrson, A.V. Bhagatwala, W.H. Cabot, and P. Moin et al. Assessment of high-resolution methods for numerical simulations of compressible turbulence with shock waves. *J. Comp. Phys.*, **229**:1213, 2010.

[2] D. Livescu and J. Ryu. Turbulent vortex dynamics after the shock-turbulence interaction. *In press Shock Waves*, 2015.

[3] K. Mahesh, S.K. Lele, and P. Moin. The influence of entropy fluctuations on the interaction of turbulence with a shock wave. *J. Fluid Mech.*, **334**:353, 1997.

[4] J. O'Brien, J. Urzay, M. Ihme, P. Moin, and A. Saghafian. Subgrid-scale backscatter in reacting and inert supersonic hydrogen-air turbulent mixing layers. *J. Fluid Mech.*, **743**:554, 2014.

[5] M.R. Petersen and D. Livescu. Forcing for statistically stationary compressible isotropic turbulence. *Phys. Fluids*, **22**:116101, 2010.

[6] J. Ryu and D. Livescu. Turbulence structure behind the shock in canonical shock-vortical turbulence interaction. *J. Fluid Mech.*, **756**:R1, 2014.

[7] J. Ryu and D. Livescu. Turbulent vortex dynamics across a normal shock. In *Proceedings of the 21st International Shock Interaction Symposium*, pages 85–90. 2014.