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High Order Numerical Methods for the Dynamic SGS Model of Turbulent Flows with Shocks

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Abstract. Simulation of turbulent flows with shocks employing subgrid-scale (SGS) filtering may encounter a loss of accuracy in the vicinity of a shock. This paper addresses the accuracy improvement of LES of turbulent flows in two ways: (a) from the SGS model standpoint and (b) from the numerical method improvement standpoint. In an internal report, Kotov et al. ("High Order Numerical Methods for large eddy simulation (LES) of Turbulent Flows with Shocks", CTR Tech Brief, Oct. 2014, Stanford University), we performed a preliminary comparative study of different approaches to reduce the loss of accuracy within the framework of the dynamic Germano SGS model. The high order low dissipative method of Yee & Sjögreen (2009) using local flow sensors to control the amount of numerical dissipation where needed is used for the LES simulation. The considered improved dynamics model approaches include applying the one-sided SGS test filter of Sagaut & Germano (2005) and/or disabling the SGS terms at the shock location. For Mach 1.5 and 3 canonical shock-turbulence interaction problems, both of these approaches show a similar accuracy improvement to that of the full use of the SGS terms. The present study focuses on a five levels of grid refinement study to obtain the reference direct numerical simulation (DNS) solution for additional LES SGS comparison and approaches. One of the numerical accuracy improvements included here applies Harten's subcell resolution procedure to locate and sharpen the shock, and uses a one-sided test filter at the grid points adjacent to the exact shock location.

AMS subject classifications: 65Z05, 65M06, 65M50, 65M55, 65M60, 65M99, 65Y99

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1 Introduction

The presence of a shock wave in turbulent flows might cause a numerical accuracy problem in employing the subgrid-scale (SGS) filtered equations across shocks, depending on the large eddy simulation (LES) model, the grid size, as well as the shock strength. Since the majority of dynamic LES models involve filter operations, hereafter referred to as "LES filters" to distinguish them from standard "numerical filters for numerical method development", when the LES filtered equations are applied through the shock, the Rankine-Hugoniot relations are affected by the filtering operation, since the filtered variables are not discontinuous. In the present study we consider LES employing the dynamic Germano procedure [7] for calculating the model coefficients. The dynamic Germano procedure was developed for shock free turbulence. Sagaut and Germano [27] have noticed that the usual filtering procedures, based on a central SGS spatial filter that provides information from both sides, when applied around the shock, produce parasitic contributions that affect the filtered quantities. They suggested using non-centered SGS filters to avoid this nonphysical effect. In Grube & Martin [8] shock-confining filters have been proposed instead. Another approach based on the deconvolution method is considered in Adams & Stolz [1].

Aside from the subgrid scale filtering procedure, the accuracy of direct numerical simulation (DNS) and LES with shocks depends heavily on the accuracy of the numerical scheme. For the last decade high order shock-capturing methods with numerical dissipation controls have been the state-of-the-art numerical approach for DNS and LES of turbulent flows with shocks. See, for example, [12,13,15,21,22,30,33,37,38,40,42]. The majority of these methods involve flow sensors with parameter tuning applied depending on the flow type. Some of the flow sensors were designed for certain flow types and might not preserve their high accuracy when used to simulate a different flow type. In a study presented in Johnsen et al. [12], all of the shock-capturing schemes involve tuning of parameters. It appears that the Yee & Sjogreen filter scheme is not as accurate as the hybrid scheme presented in [12] as the key parameter κ responsible for minimizing the numerical dissipation in the 2007 Yee & Sjogreen scheme [38] was mandated to be the same for all considered test cases reported in [12]. See [15,40] for a description of better control of numerical dissipation using a local κ. The hybrid scheme presented in [12] which employed the Ducros et al. flow sensor [4] also consists of a key tuning parameter δ. From our study presented in [17] of the same Taylor-Green vortex problem considered in [12], the cut-off parameter δ should be set to 1 to achieve the best accurate result. On the other hand, for the isotropic turbulence with shocklets test case, the Ducros et al. flow sensor δ parameter has to be reduced, mostly by trial and error. Yet in another study [13] for turbulence interacting with a high speed stationary shock, depending on the Mach number and turbulent Mach number, a different δ is required for each case. It is noted that for LES simulation it is more important to use low-dissipative schemes as added dissipation has already introduced by the SGS model.