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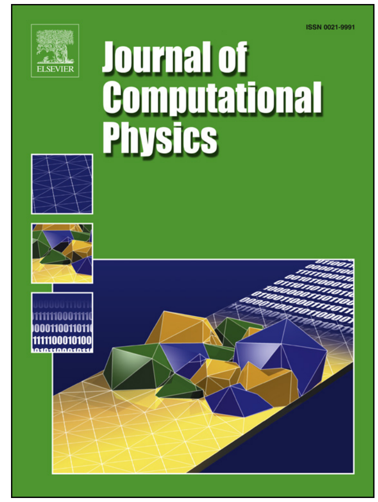

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An upwind CESE scheme for 2D and 3D MHD numerical simulation in general curvilinear coordinates

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Abstract: Shen et al. [1, 2] proposed an upwind space-time conservation element and solution element (CESE) scheme for 1D and 2D hydrodynamics (HD) in rectangular coordinates, which combined the advantages of CESE and upwind scheme, namely, guaranteed strictly the space-time conservation law as well as captured discontinuities very efficiently. All kinds of upwind schemes can be combined very flexibly for different problems to achieve the perfect combination of CESE and finite volume method (FVM). However, in many physical applications, we need to consider geometries that are more sophisticated. Hence, the main objective of this paper is to extend the upwind CESE scheme to multidimensional magneto-hydrodynamics (MHD) in general curvilinear coordinates by transforming the MHD equations from the physical domain (general curvilinear coordinates) to the computational domain (rectangular coordinates) and the new equations in the computational domain can be still written in the conservation form. For the 3D case, the derivations of some formulas are much more abstract and complex in a 4D Euclidean hyperspace, and some technical problems need to be solved in the debugging process. Unlike in HD, keeping the magnetic field divergence-free for MHD problems is also a challenge especially in general curvilinear coordinates. These are the main obstacles we have overcome in this study. The test results of benchmarks demonstrate that we have successfully extended the upwind CESE scheme to general curvilinear coordinates for both 2D and 3D MHD problems.

Keywords: upwind; CESE scheme; MHD; curvilinear coordinates; transforming; divergence-free

1. Introduction

Some complex flow phenomena such as shock and other discontinuities as well as shear layers are often met with for HD and MHD problems. Many researchers have tried their best to design schemes which can maximize accuracy and robustness in dealing with complex flow problems. Upwind schemes are most popular in dealing with discontinuous problems, and these can be split into three groups [3, 4]: flux vector splitting (FVS), flux difference splitting (FDS) and CUSP family (including AUSM [5, 6], CUSP [7-11], LDFSS [12], AUFS [13]). In fact, CUSP family are special FVS schemes. The usually used FVS schemes mainly include three types for HD [4]: Steger-Warming [14], Lax-Friedrichs [15], and Van-Leer [16] splitting. MacCormack [17] developed an FVS method for MHD to overcome the challenge of inhomogeneous coefficient matrices of MHD equations. The usually used FDS schemes mainly include HLL [18-21], HLLC [20] [22-25], HLLD [26-27], Roe [23] [28, 29] and one TVD scheme proposed by Balsara [30] which is based on a linearized formulation of the Riemann problem [31, 32]. Later, some new hybrid schemes were developed, combining two or more isolated schemes to obtain a better scheme than just using any one of these schemes. Up to now, we have known mainly three types of hybrid schemes: Hybrid flux-splitting schemes [33-38]; PISO+AUSM [39, 40]; Rotated Riemann solver [41-43]. The

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