

Positivity-preserving pseudo arc-length method for solving extreme explosive shock wave flow field problems in hyperbolic conservation law equations

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ABSTRACT

Hyperbolic conservation law equation is a system of partial differential equations, which has the characteristics of hyperbolic type, and its solution will eventually evolve into a singular solution with strong discontinuity and weak discontinuity. In solving hyperbolic conservation law equations, in addition to eliminating or reducing the singularity of the equation, it is also involved in solving the problems of high density ratios, high pressure ratios, low densities, and low pressures in extreme explosive shock wave flow field. The numerical solution process often produces negative density, negative pressure, or negative internal energy, which in turn triggers nonlinear instabilities in the region of large gradients, eventually leading to termination of the computational procedure. To effectively solve the above difficulties and improve the robustness of the algorithm, this paper proposes a high-order accuracy pseudo arc length method (PALM) with positivity-preserving for solving hyperbolic conservation law equations. The core idea of the algorithm introduces arc length constraint equations to realize the smooth transition of physical quantities with large gradients in the original physical space in the computational arc length space, so as to eliminate or attenuate the singularity of the discontinuous solutions in the computational process. In the orthogonal pseudo arc length coordinate system, a new weighted essentially non-oscillatory- α scheme with a global smoothness indicator is used for high-order reconstruction, effectively addressing the issue of nonphysical oscillations caused by high-order schemes. In addition, the positivity-preserving limiter of the high-order pseudo arc length adaptive method in the arc length computational coordinate system is further constructed and proved, and the grid motion limiting strategy is designed, which greatly enhances the reliability and robustness of the algorithm. Finally, numerical test results show that the PALM effectively reduces numerical oscillations and achieves high-resolution capture of discontinuity problems.

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1. INTRODUCTION

Hyperbolic conservation law equations play a key role in fields such as physics, engineering, and applied mathematics, and are widely used to describe complex physical phenomena. For example, in fluid dynamics to describe the flow of gases and fluids, in elasticity to characterize the propagation of elastic waves, in quantum mechanics to describe the evolution of wave functions,^{1–3} etc. The usual form of such equations is hyperbolic partial differential equations, possessing specific structural features. Their mathematical properties allow for sharp variations in the solutions, enabling the formation of sharp shock waves. Therefore, they are extremely effective in modeling rapidly changing physical processes such as shock wave propagation in extreme explosive shock wave flow problems. It is generally believed

that despite smooth initial conditions, solutions to hyperbolic conservation law equations tend to exhibit discontinuities during evolution.⁴ These discontinuities usually appear as discontinuities in the form of shock waves, contact discontinuities, or sparse waves. Therefore, the numerical solution of hyperbolic conservation laws mainly focuses on eliminating or reducing singularities⁵ and accurately capturing discontinuities or regions with large gradients in the flow field.

For the capture of sharp shock waves in the flow field and the fine solution of complex flow field wave system structures, a large number of formats were designed by early scholars. Godunov⁶ designed a first-order Godunov format to solve the related problems based on the physical properties of the flow and from the concept of discontinuity decomposition. Subsequently, van Leer⁷ improved the

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