

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

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Kun Li (李坤)¹  Tianbao Ma (马天堡)^{1,2,✉}  and Chentao Wang (王晨涛)² 

AFFILIATIONS

¹State Key Laboratory of Explosion Science and Safety Protection, Beijing Institute of Technology, Beijing 100081, China

²Chinese Aeronautical Establishment, Beijing 100012, China

[✉]Author to whom correspondence should be addressed: madabao@bit.edu.cn

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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Table of Contents Solving Athletic Field Problems J R Watson

1. Understanding the eBook Solving Athletic Field Problems J R Watson
 - The Rise of Digital Reading Solving Athletic Field Problems J R Watson
 - Advantages of eBooks Over Traditional Books
2. Identifying Solving Athletic Field Problems J R Watson
 - Exploring Different Genres
 - Considering Fiction vs. Non-Fiction
 - Determining Your Reading Goals
3. Choosing the Right eBook Platform
 - Popular eBook Platforms
 - Features to Look for in an Solving Athletic Field Problems J R Watson
 - User-Friendly Interface
4. Exploring eBook Recommendations from Solving Athletic Field Problems J R Watson
 - Personalized Recommendations
 - Solving Athletic Field Problems J R Watson User Reviews and Ratings
 - Solving Athletic Field Problems J R Watson and Bestseller Lists

5. Accessing Solving Athletic Field Problems J R Watson Free and Paid eBooks
 - Solving Athletic Field Problems J R Watson Public Domain eBooks
 - Solving Athletic Field Problems J R Watson eBook Subscription Services
 - Solving Athletic Field Problems J R Watson Budget-Friendly Options
6. Navigating Solving Athletic Field Problems J R Watson eBook Formats
 - ePub, PDF, MOBI, and More
 - Solving Athletic Field Problems J R Watson Compatibility with Devices
 - Solving Athletic Field Problems J R Watson Enhanced eBook Features
7. Enhancing Your Reading Experience
 - Adjustable Fonts and Text Sizes of Solving Athletic Field Problems J R Watson
 - Highlighting and Note-Taking Solving Athletic Field Problems J R Watson
 - Interactive Elements Solving Athletic Field Problems J R Watson
8. Staying Engaged with Solving Athletic Field Problems J R Watson
 - Joining Online Reading Communities
 - Participating in Virtual Book Clubs
 - Following Authors and Publishers Solving Athletic Field Problems J R Watson
9. Balancing eBooks and Physical Books Solving Athletic Field Problems J R Watson
 - Benefits of a Digital Library
 - Creating a Diverse Reading Collection Solving Athletic Field Problems J R Watson
10. Overcoming Reading Challenges
 - Dealing with Digital Eye Strain
 - Minimizing Distractions
 - Managing Screen Time
11. Cultivating a Reading Routine Solving Athletic Field Problems J R Watson
 - Setting Reading Goals Solving Athletic Field Problems J R Watson
 - Carving Out Dedicated Reading Time
12. Sourcing Reliable Information of Solving Athletic Field Problems J R Watson
 - Fact-Checking eBook Content of Solving Athletic Field Problems J R Watson
 - Distinguishing Credible Sources
13. Promoting Lifelong Learning

- Utilizing eBooks for Skill Development
 - Exploring Educational eBooks
14. Embracing eBook Trends
- Integration of Multimedia Elements
 - Interactive and Gamified eBooks

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