

NUMERICAL MAGNETOHYDRODYNAMICS

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ABSTRACT

The ideal MagnetoHydroDynamic (MHD) equations accurately describe the macroscopic dynamics of a perfectly conducting plasma. Adopting a continuum, single fluid description in terms of the plasma density ρ , velocity \mathbf{v} , thermal pressure p and magnetic field \mathbf{B} , the ideal MHD system expresses conservation of mass, momentum, energy, and magnetic flux. This nonlinear, conservative system of 8 partial differential equations enriches the Euler equations governing the dynamics of a compressible gas with the dynamical influence – through the Lorentz force – and evolution – through the additional induction equation – of the magnetic field \mathbf{B} . In multi-dimensional problems, the topological constraint expressed by the Maxwell equation $\nabla \cdot \mathbf{B} = 0$, represents an additional complication for numerical MHD. Basic concepts of shock-capturing high-resolution schemes for computational MHD are presented, with an emphasis on how they cope with the tight physical demands resulting from nonlinearity, compressibility, conservation, and solenoidality.

1. LINEAR ADVECTION PROBLEM

As a preliminary to the full Euler and MHD system addressed below, it is instructive to focus on a seemingly trivial problem at first, namely the numerical solution to the advection equation in 1 spatial (x) dimension given by

$$\partial_t \rho + v \partial_x \rho = 0. \quad (1)$$

Under a constant given velocity v , an initial density pulse $\rho(x, t = 0) = \rho_0(x)$ will merely be advected at the constant speed, such that $\rho(x, t) = \rho_0(x - vt)$. Analytically, we are done.

Numerically, we need to discretize the problem both spatially and temporally, and come up with a recipe to advance the discrete solution ρ_i^n on grid cells indexed by i from time level t_n to t_{n+1} . A forward Euler

temporal discretization, combined with a centered difference spatial gradient approximation, suggests as a time-stepping recipe:

$$\frac{\rho_i^{n+1} - \rho_i^n}{\Delta t} + v \frac{\rho_{i+1}^n - \rho_{i-1}^n}{2\Delta x} = 0. \quad (2)$$

Unfortunately, this method leads unavoidably to a numerical instability, under all combinations of time step Δt and grid size Δx . This can be predicted by a Von Neumann stability analysis of the discrete formula (2), which inserts $\rho(x, t_n) = G^n \rho_0 e^{ikx}$ and computes the amplification factor $|G|$ defined from $\rho^{n+1} = \frac{G^{n+1}}{G^n} \rho^n = G \rho^n$. The unconditional instability of the method is found from $|G| > 1$ for all wavenumbers k .

Luckily, there are several ways to ‘cure’ the instability (at least conditionally) by slightly modifying the formula (2). One way is to replace the centered difference spatial gradient by a one-sided gradient operator, taken in the ‘upwind’ direction. That is, if the flow goes from left to right ($v > 0$), simply use the upwind scheme

$$\frac{\rho_i^{n+1} - \rho_i^n}{\Delta t} + v \frac{\rho_i^n - \rho_{i-1}^n}{\Delta x} = 0. \quad (3)$$

A method which mixes spatially forward and backward differences as follows

$$\begin{aligned} \rho_i^* &= \rho_i^n - \frac{\Delta t}{\Delta x} v (\rho_{i+1}^n - \rho_i^n) \\ \rho_i^{n+1} &= \rho_i^n - \frac{\Delta t}{\Delta x} v (\rho_i^* - \rho_{i-1}^n) \\ \rho_i^{n+1} &= \frac{\rho_i^n + \rho_i^*}{2} \end{aligned} \quad (4)$$

is known as the MacCormack method, and this can be rewritten as

$$\begin{aligned} \rho_i^{n+1} &= \rho_i^n - \frac{\Delta t}{\Delta x} v \left(\frac{\rho_{i+1}^n - \rho_{i-1}^n}{2} \right) \\ &\quad + \frac{(\Delta t)^2}{(\Delta x)^2} v^2 \left(\frac{\rho_{i-1}^n - 2\rho_i^n + \rho_{i+1}^n}{2} \right). \end{aligned} \quad (5)$$

Hence, while the upwind method (3) stabilizes the scheme (2) by replacing the centered spatial gradient

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Roger J. Hosking, Robert L. Dewar



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