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Stable Numerical Scheme for the Magnetic Induction Equation with Hall Effect

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Abstract

Fast magnetic reconnection can be modeled by Hall MHD equations. We consider a sub-model: the Hall induction equations and design stable finite difference schemes to approximate it. Numerical examples are provided to verify the robustness of the scheme.

1 Introduction

Magnetic reconnection, a widely studied phenomena in plasma physics, is a change of topology of the magnetic field lines that permits a fast change of the magnetic energy into thermal and kinetic energy. One of popular models for fast reconnection [1], are the equations of the form :

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \mathbf{u}) \tag{1.1}$$

$$\frac{\partial (\rho \mathbf{u})}{\partial t} = -\nabla \left\{ \rho \mathbf{u} \otimes \mathbf{u} + \left(p + \frac{|\mathbf{B}|^2}{2} \right) \mathbf{I}_{3\times 3} - \mathbf{B} \otimes \mathbf{B} \right\} \tag{1.2}$$

$$\frac{\partial \mathcal{E}}{\partial t} = -\nabla \left\{ \left(\mathcal{E} + p + \frac{|\mathbf{B}|^2}{2} \right) \mathbf{u} + \mathbf{E} \times \mathbf{B} \right\} \tag{1.3}$$

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}. \tag{1.4}$$

Here ρ, $\mathbf{u}$, p are the gas density, velocity and pressure respectively. $\mathbf{E}$ and $\mathbf{B}$ are the electric and magnetic fields. The total energy $\mathcal{E}$ is given by the equation of state, i.e.,

$$\mathcal{E} = \frac{p}{\gamma - 1} + \frac{\rho |\mathbf{u}|^2}{2} + \frac{|\mathbf{B}|^2}{2}. \tag{1.5}$$

Here γ is the gas constant. Equations from (1.1) to (1.3) represent the conservation of mass, momentum and energy; the last one (1.4) describes

the evolution of the magnetic field.
The equations have to obey the divergence constraint:

$$\nabla \cdot \mathbf{B} = 0. \tag{1.6}$$

For ideal MHD, the electric field is given by

$$\mathbf{E} = -\mathbf{u} \times \mathbf{B}. \tag{1.7}$$

However, no reconnection is possible with this model. In order to model fast reconnection, we use a generalized Ohm's law [2],[3]

$$\mathbf{E} = -\mathbf{u} \times \mathbf{B} + \eta \mathbf{J} + \frac{\delta_i}{L_0} \frac{\mathbf{J} \times \mathbf{B}}{\rho} + \left(\frac{\delta_e}{L_0} \right)^2 \frac{1}{\rho} \left[\frac{\partial \mathbf{J}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{J} \right]. \tag{1.8}$$

Here L_0 is the normalizing length unit, and δ_e and δ_i denote electron and ion inertia respectively; they are related to electron-ion mass ratio by $(\frac{\delta_e}{\delta_i})^2 = \frac{m_e}{m_i}$.
Using the Ampère's law we can write the electric current $\mathbf{J}$ as

$$\mathbf{J} = \nabla \times \mathbf{B}. \tag{1.9}$$

The Hall MHD equations are non-linear and complicated. A sub-model is the Hall induction equation given by

$$\begin{aligned} \frac{\partial}{\partial t} \left[\mathbf{B} + \left(\frac{\delta_e}{L_0} \right)^2 \nabla \times (\nabla \times \mathbf{B}) \right] &= \nabla \times (\mathbf{u} \times \mathbf{B}) - \eta \nabla \times (\nabla \times \mathbf{B}) \\ - \left(\frac{\delta_e}{L_0} \right)^2 \frac{1}{\rho} \nabla \times ((\mathbf{u} \cdot \nabla)(\nabla \times \mathbf{B})) &- \frac{\delta_i}{L_0} \frac{1}{\rho} \nabla \times ((\nabla \times \mathbf{B}) \times \mathbf{B}) \end{aligned} \tag{1.10}$$

with $\mathbf{u}$ being a given velocity field.
For the remaining part of this paper, we will focus on the Hall induction equations (1.10) and onto the design stable numerical scheme for it.

2 Theoretical Analysis

We rewrite the advection term in (1.10) using a standard vector identity resulting in

$$\nabla \times (\mathbf{u} \times \mathbf{B}) = (\mathbf{B} \cdot \nabla)\mathbf{u} - \mathbf{B}(\nabla \cdot \mathbf{u}) + \mathbf{u}(\nabla \cdot \mathbf{B}) - (\mathbf{u} \cdot \nabla)\mathbf{B} \tag{2.1}$$

We note that the term that leads to a lack of symmetry is $\mathbf{u}(\nabla \cdot \mathbf{B})$. For divergence free data (1.6) this term vanishes and the remaining equations are in symmetric form:

$$\frac{\partial}{\partial t}\left[\mathbf{B}+\left(\frac{\delta_e}{L_0}\right)^2\nabla\times(\nabla\times\mathbf{B})\right]=(\mathbf{B}\cdot\nabla)\mathbf{u}-\mathbf{B}(\nabla\cdot\mathbf{u})-(\mathbf{u}\cdot\nabla)\mathbf{B}$$
$$-\eta\nabla\times(\nabla\times\mathbf{B})-\left(\frac{\delta_e}{L_0}\right)^2\frac{1}{\rho}\nabla\times((\mathbf{u}\cdot\nabla)(\nabla\times\mathbf{B}))$$
$$-\frac{\delta_i}{L_0}\frac{1}{\rho}\nabla\times((\nabla\times\mathbf{B})\times\mathbf{B}) \tag{2.2}$$

We have the following theorem:

Theorem 2.1. *Let* $\mathbf{u}\in C^2(\mathbb{R}^3)$ *decays to zero sufficiently fast. Furthermore, assume that the solution of (2.2) goes to zero at infinity, then following apriori estimates hold:*

$$\frac{d}{dt}\left(\|\mathbf{B}\|^2_{L^2(\mathbb{R}^3)}+\left(\frac{\delta_e}{L_0}\right)^2\frac{1}{\rho}\|\nabla\times\mathbf{B}\|^2_{L^2(\mathbb{R}^3)}\right)$$
$$\le C_1\left(\|\mathbf{B}\|^2_{L^2(\mathbb{R}^3)}+\left(\frac{\delta_e}{L_0}\right)^2\frac{1}{\rho}\|\nabla\times\mathbf{B}\|^2_{L^2(\mathbb{R}^3)}\right) \tag{2.3}$$

$$\frac{d}{dt}\|\nabla\cdot\mathbf{B}\|_{L^2(\mathbb{R}^3)}\le C_2\|\nabla\cdot\mathbf{B}\|_{L^2(\mathbb{R}^3)} \tag{2.4}$$

with C_1 *and* C_2 *being constants that depend on* $\mathbf{u}$ *and its derivatives only. The above estimates imply that* $\mathbf{B}\in H^1_{loc}(\mathbb{R}^3)$.

Proof. For the first inequality we multiply the equation with $\mathbf{B}$ and then integrate over $\mathbb{R}^3$ resulting in

$$\int_{\mathbb{R}^3}\frac{1}{2}\frac{\partial\mathbf{B}^2}{\partial t}+\left(\frac{\delta_e}{L_0}\right)^2\frac{1}{\rho}\mathbf{B}\nabla\times(\nabla\times\frac{\partial\mathbf{B}}{\partial t})dx=$$
$$\int_{\mathbb{R}^3}\left[\mathbf{B}(\mathbf{B}\cdot\nabla)\mathbf{u}-\mathbf{B}^2(\nabla\cdot\mathbf{u})-\frac{1}{2}(\mathbf{u}\cdot\nabla)\mathbf{B}^2-\eta\mathbf{B}\nabla\times(\nabla\times\mathbf{B})\right.$$
$$\left.-\left(\frac{\delta_e}{L_0}\right)^2\frac{1}{\rho}\mathbf{B}\nabla\times((\mathbf{u}\cdot\nabla)(\nabla\times\mathbf{B}))-\frac{\delta_i}{L_0}\frac{1}{\rho}\mathbf{B}\nabla\times((\nabla\times\mathbf{B})\times\mathbf{B})\right]dx.$$

Partial integration yields

$$\frac{1}{2}\frac{d}{dt}\left(\|\mathbf{B}\|^2_{L^2(\mathbb{R}^3)}+\left(\frac{\delta_e}{L_0}\right)^2\|\nabla\times\mathbf{B}\|^2_{L^2(\mathbb{R}^3)}\right)=$$
$$\int_{\mathbb{R}^3}\left[\mathbf{B}(\mathbf{B}\cdot\nabla)\mathbf{u}-\frac{1}{2}\mathbf{B}^2(\nabla\cdot\mathbf{u})-\eta(\nabla\times\mathbf{B})^2\right.$$
$$\left.+\frac{1}{2}\left(\frac{\delta_e}{L_0}\right)^2\frac{1}{\rho}(\nabla\cdot\mathbf{u})(\nabla\times\mathbf{B})^2-\frac{\delta_i}{L_0}\frac{1}{\rho}\underbrace{(\nabla\times\mathbf{B})((\nabla\times\mathbf{B})\times\mathbf{B})}_{=0}\right]dx$$

Using the smoothness of u in the above identity leads to

$$\frac{d}{dt}\left(\|\mathbf{B}\|^2_{L^2(\mathbb{R}^3)} + \left(\frac{\delta_e}{L_0}\right)^2 \|\nabla \times \mathbf{B}\|^2_{L^2(\mathbb{R}^3)}\right) \leq$$

$$C_A\|\mathbf{B}\|^2_{L^2(\mathbb{R}^3)} + C_B\left(\frac{\delta_e}{L_0}\right)^2 \|\nabla \times \mathbf{B}\|^2_{L^2(\mathbb{R}^3)}$$

here $C_A = \max_{k=\{x,y,z\}}(\|\frac{\partial(u_1+u_2+u_3)}{\partial k}\|_{L^\infty(\mathbb{R}^3)})$ and $C_B = \|\nabla \mathbf{u}\|_{L^\infty(\mathbb{R}^3)}$. Applying divergence operator on (2.2), we obtain

$$\frac{\partial \nabla \cdot \mathbf{B}}{\partial t} = -\nabla(\mathbf{u}(\nabla \cdot \mathbf{B})).$$

Integrating over $\mathbb{R}^3$ and then integration by parts, we obtain the estimate (2.4) by setting $C_2 = \|\nabla \mathbf{u}\|_{L^\infty(V)}$. □

3 Numerical Scheme

We subdivide the computational domain using a uniform Cartesian mesh with mesh width Δx,Δy and Δz. $\hat{\mathbf{B}}_{i,j,k}(t)$ and $\hat{\mathbf{u}}_{i,j,k}(t)$ are approximations of $\mathbf{B}(\mathbf{x},t)$ and $\mathbf{u}(\mathbf{x},t)$ at point (x_i, y_j, z_k). We also define discrete derivatives $\mathbf{D} = (D_x, D_y, D_z)^\top$ using central differences:

$$\begin{pmatrix} D_x \\ D_y \\ D_z \end{pmatrix} a_{i,j,k} = \begin{pmatrix} \frac{a_{i+1,j,k}-a_{i-1,j,k}}{2\Delta x}. \\ \frac{a_{i,j+1,k}-a_{i,j-1,k}}{2\Delta y}. \\ \frac{a_{i,j,k+1}-a_{i,j,k-1}}{2\Delta z}. \end{pmatrix} \tag{3.1}$$

where $a_{i,j,k}$ is an arbitrary function defined on the mesh. For central difference operators we have the following lemmas:

Lemma 3.1 (Summation by parts). *Let $a_{i,j,k}$ and $b_{i,j,k}$ be grid functions, such that $|a_{i,j,k}|, |b_{i,j,k}| \to 0$ for $i, j, k \to \infty$ then*

$$\sum_{i,j,k} a_{i,j,k} D_x b_{i,j,k} = -\sum_{i,j,k} b_{i,j,k} D_x a_{i,j,k} \tag{3.2}$$

Proof. This follow directly by a change of index in the sum. □

Lemma 3.2 (Discrete chain rule). *For every finite difference operator D that approximates the first derivative, there exists an averaging operator A such that for every $a_{i,j,k} = a(x_i, y_j, z_k)$ with $a \in C^2$ and every $b_{i,j,k}$ defined on the mesh,*

$$D(a_{i,j,k}b_{i,j,k}) = a_{i,j,k}D(b_{i,j,k}) + A(b_{i,j,k})D(a_{i,j,k}) + \tilde{a}_{i,j,k} \tag{3.3}$$

holds. If $b_{i,j,k} \in l^2$, then the residual $\tilde{a}$ is bounded i.e., $\|\tilde{a}\| \leq Ch\|b\|$ for a generic mesh size h and some constant $C > 0$.

Proof. For the proof of this lemma, see [4] lemma 3.3. □

For approximating (2.2) we use the following semi-discrete numerical scheme

$$\frac{\partial}{\partial t}\left[\hat{\mathbf{B}}_{i,j,k} + \left(\frac{\delta_e}{L_0}\right)^2 \mathbf{D}\times(\mathbf{D}\times\hat{\mathbf{B}}_{i,j,k})\right] = \bar{\mathbf{A}}\left(\hat{\mathbf{B}}_{i,j,k}\cdot\mathbf{D}\right)\hat{\mathbf{u}}_{i,j,k}$$
$$-\mathbf{A}\left(\hat{\mathbf{B}}_{i,j,k}(\mathbf{D}\cdot\hat{\mathbf{u}}_{i,j,k})\right) - (\hat{\mathbf{u}}_{i,j,k}\cdot\mathbf{D})\hat{\mathbf{B}}_{i,j,k} - \eta\mathbf{D}\times(\mathbf{D}\times\hat{\mathbf{B}}_{i,j,k})$$
$$-\left(\frac{\delta_e}{L_0}\right)^2\frac{1}{\rho}\mathbf{D}\times((\hat{\mathbf{u}}_{i,j,k}\cdot\mathbf{D})\hat{\mathbf{B}}_{i,j,k}) - \frac{\delta_i}{L_0}\frac{1}{\rho}\mathbf{D}\times\left((\mathbf{D}\times\hat{\mathbf{B}}_{i,j,k})\times\hat{\mathbf{B}}_{i,j,k}\right). \tag{3.4}$$

Note that t is suppressed for notational convenience. We denote

$$\bar{\mathbf{A}}(\mathbf{B}_{i,j,k}\cdot\mathbf{D}) = A_x(B^1_{i,j,k})D_x + A_y(B^2_{i,j,k})D_y + A_z(B^3_{i,j,k})D_z \tag{3.5}$$

and

$$\mathbf{A}\left(\mathbf{B}_{i,j,k}(\mathbf{D}\cdot\mathbf{u}_{i,j,k})\right)^i =$$
$$A_x(B^i_{i,j,k})D_x u^1_{i,j,k} + A_y(B^i_{i,j,k})D_y u^2_{i,j,k} + A_z(B^i_{i,j,k})D_z u^3_{i,j,k} \tag{3.6}$$

for $i = 1, 2, 3$. A being the averaging operator defined in previous lemma. We can show that the following holds:

Theorem 3.3. *Let $\hat{\mathbf{u}}_{i,j,k} = \mathbf{u}(x_i, y_j, z_k)$ be the point evaluation of a function $u \in C^2$ and let the solutions of (3.4) go to zero at infinity, then the following estimates hold*

$$\frac{d}{dt}\left(\|\hat{\mathbf{B}}\|^2_{l^2(\mathbb{R}^3)} + \left(\frac{\delta_e}{L_0}\right)^2\frac{1}{\rho}\|\mathbf{D}\times\hat{\mathbf{B}}\|^2_{l^2(\mathbb{R}^3)}\right)$$
$$\leq C_1\left(\|\hat{\mathbf{B}}\|^2_{l^2(\mathbb{R}^3)} + \left(\frac{\delta_e}{L_0}\right)^2\frac{1}{\rho}\|\mathbf{D}\times\hat{\mathbf{B}}\|^2_{l^2(\mathbb{R}^3)}\right) \tag{3.7}$$

$$\frac{d}{dt}\|\mathbf{D}\cdot\hat{\mathbf{B}}\|^2_{l^2(\mathbb{R}^3)} \leq C_2\|\mathbf{D}\cdot\hat{\mathbf{B}}\|^2_{l^2(\mathbb{R}^3)} + C_3\max(\Delta x, \Delta y, \Delta z) \tag{3.8}$$

with C_1, C_2 and C_3 constant that depend on **u** *and its derivative only.*

Proof. The proof of this theorem uses the two lemmas 3.1 and 3.2 to mimic the proof of the continuous version of this theorem (Thm. 2.1). A detailed proof will be provided in [5]. □

The scheme (3.4) is semi-discrete and needs to be coupled with a suitable numerical time-integration routine. We have chosen to use a second-order SSP Runge-Kutta method [6].

Remark 3.4. A fourth order version of this scheme is derived by replacing the central difference operator by corresponding fourth-order central difference, e.g.,

$$D_x^{(4)} a_{i,j,k} = \frac{2}{3}\frac{a_{i+1,j,k} - a_{i-1,j,k}}{\Delta x} - \frac{1}{12}\frac{a_{i+2,j,k} - a_{i-2,j,k}}{\Delta x} \tag{3.9}$$

4 Numerical Experiments

We tested the numerical scheme for a 2-d version of the general induction equations(2.2) with the following initial data

$$\mathbf{B}_0(x, y) = 4 \begin{pmatrix} -y \\ x - \frac{1}{2} \\ 0 \end{pmatrix} e^{-20((x-\frac{1}{2})^2+y^2)} \tag{4.1}$$

and $\mathbf{u} = (-y, x, 0)^\top$. An exact solution of this problem can be calculated in the pure advection case, i.e. if $\eta = \delta_i = \delta_e = 0$. The solution is given by

$$\mathbf{B}(x, y, t) = \mathbf{R}(t)\mathbf{B}_0(\mathbf{R}(-t)(x, y)) \tag{4.2}$$

where $\mathbf{R}(t)$ is a rotation matrix on the z axis with angular velocity t. We ran two different tests on the domain $[-2.5, 2.5] \times [-2.5, 2.5]$ with Dirichlet boundary conditions.

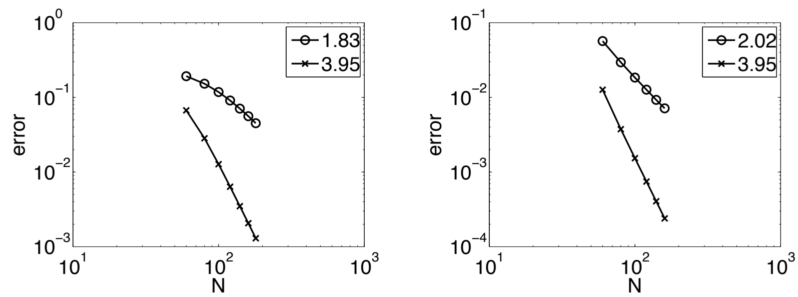

Figure 4.1: l^2 convergence analysis. On the left we have $\eta = \delta_i = \delta_e = 0$, and on the right the forced problem for $L_0 = \rho = 1$, $\eta = 0.01$,$\delta_i = 0.1$ and $\delta_e = 4.5 \times 10^{-2}$. In the legend we show the slope of the lines

Test 1 We test convergence of the scheme for two different central difference operators. One of second order and other of order four.
In absence of a known analytical solution in presence of Hall effect, we have modified the problem. We add known analytical source

term to the induction equation; this term is computed so that (4.2) is the solution of the forced version of (2.2).
In Fig. 4.1 we show l^2 errors after a time $t = 2\pi$ for different mesh size $N = N_x = N_y$. The theoretical orders of convergence are obtained.

Test 2 As second test we compare the solutions for advection problem and full problem at time $t = \pi$ (Fig.4.2). We note that that the resistivity and the Hall term diffuse the solution and also induce a creation of a small third component in the field.

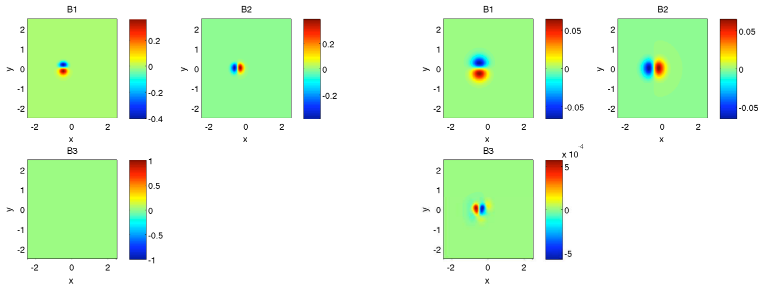

Figure 4.2: Solution after $T = \pi$. On the left we have $\eta = \delta_i = \delta_e = 0$, and on the right we have $L_0 = \rho = 1$, $\eta = 0.01$,$\delta_i = 0.1$ and $\delta_e = 4.5 \times 10^{-2}$.

5 Conclusion

The symmetric form of the general induction equations (2.2) posses some energy and divergence estimates. These estimates can be used to build a stable numerical scheme.
The presence of a time-derivative of the current in (2.2) implies that a matrix inversion has to be performed at every time step. Currently, we use a direct solver to invert the matrix. However, the matrix is ill conditioned and suitable pre-conditioners need to be devised to stabilize and accelerate the inversion algorithms. The design of such pre-conditioner is a topic of ongoing research and they will be presented in forthcoming papers.

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