Patterns of MHD Perturbations Driven by Three-Dimensional Time-Dependent Magnetic Reconnection in a Compressible Plasma

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Abstract

An analytical theory of three dimensional time dependent Petschek type reconnection in compressible plasma with skewed fields, plasma velocities and X–line of finite length is used to calculate and explain patterns of perturbations of the magnetic field, pressure, mass density, and plasma velocity at various positions of a satellite in relation to a current sheet and X–line. In our model it is assumed that all dissipative processes responsible for reconnection are localized in an idealized reconnection line of effective finite length and can be taken into account by specifying a time and space varying reconnection rate. An electric field pulse launches a series of large amplitude non–linear MHD waves which redistribute the initial current, form a structured region with accelerated and heated plasma inside and excite disturbances in the surrounding media.

1 Introduction

Magnetic field line reconnection is a fundamental plasma process which is important in numerous cases such as the solar wind interaction with planetary magnetospheres, the energy release in solar flares, transport processes in fusion devices, etc. The 'fast' reconnection model originally proposed by Petschek [1] considers the global evolution of magnetic flux tubes which have been locally reconnected across an initially magnetically closed current carrying surface. In terms of ideal magnetohydrodynamics (MHD) this is described as a broken tangential discontinuity: a local dissipative electric field [2] tangential to the surface leads to a "breaking" and "reconnection" of magnetic flux tubes. The tangential electric field itself is then transported over the surface by large amplitude MHD waves. This leads to an effective nonlinear release of energy stored within the current surface. More specifically, the surface breaks into a thin boundary layer (BL) which collects plasma from the adjacent reconnected flux tubes and accelerates this plasma to Alfvèn speed velocities.

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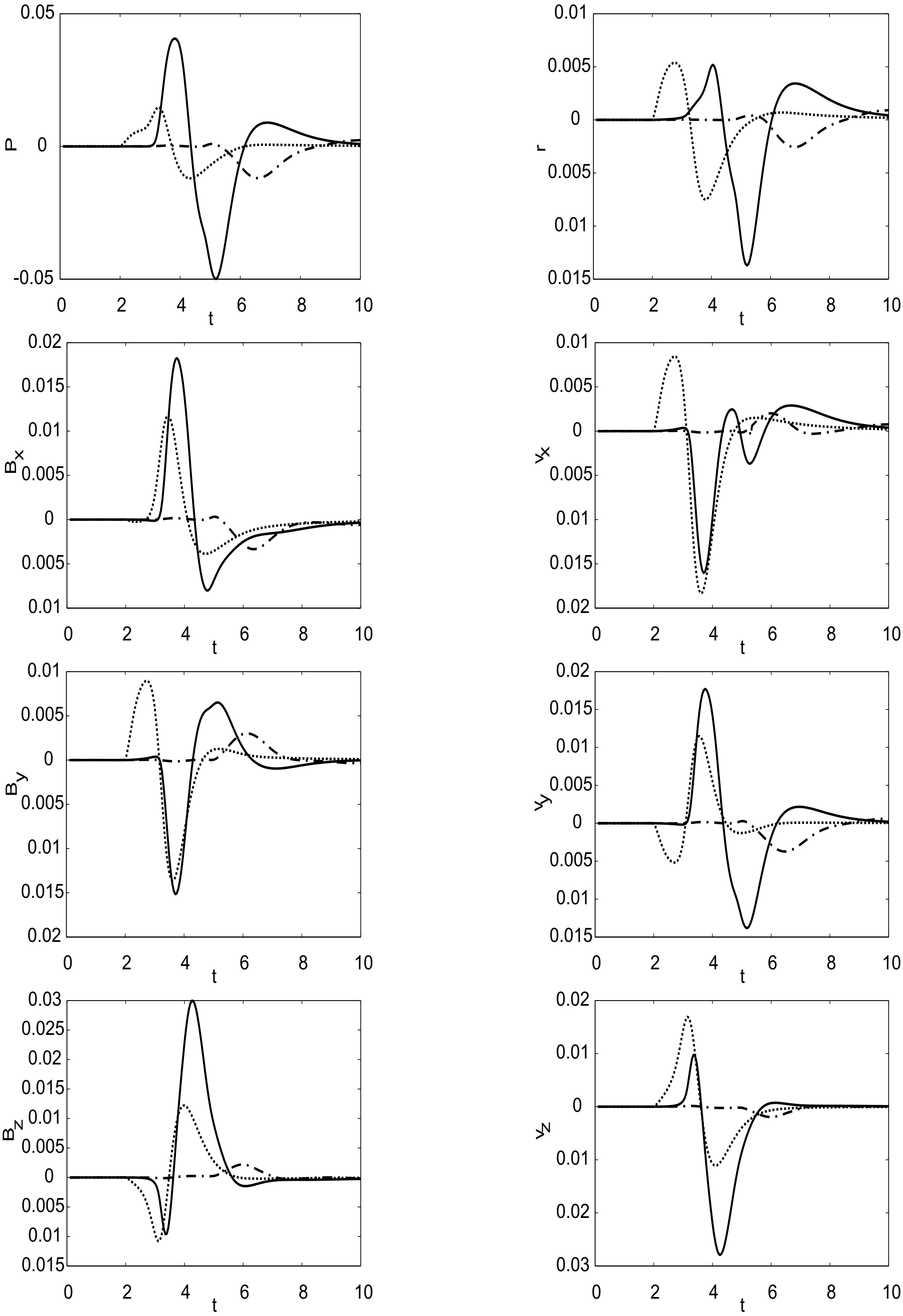

Figure 1: Shown are time series of the MHD perturbations for reconnection in skewed magnetic fields at $x = 3$, $z = 0.5$ and $y = 0$ (solid curves), $y = 3$ (dotted curves), $y = 6$ (dashed–dotted curves) as functions of time.

In the present study, the shape as well as the spatial localization of the reconnection electric field is assumed a priori and from this the plasma flow and magnetic field in the outer, ideal region is computed. The perturbations in form of shocks and discontinuities moving within the BL act as sources for the perturbations in the surrounding medium. The solution in these outer regions is found from the solution of the linearized compressible ideal MHD set of equations supplemented with the appropriate boundary conditions, in particular, total pressure balance as well as mass and magnetic flux conservation at the location of the initial current surface ($z = 0$).

In the present paper it is shown how to construct the outer solution of time varying reconnection of magnetic flux tubes in a compressible plasma. Results for reconnection in a skewed magnetic field structure are presented in order to illustrate the method.

2 Model description

Once magnetic flux had been reconnected locally along some idealized line within a current surface, the big scale evolutions of the process can be described in the framework of ideal magnetohydrodynamics [3]. When the ideal MHD equations are linearized with respect to constant background quantities, all first order MHD quantities can be derived from a displacement vector [4]. After some algebra [5], the displacement vector is found to be

$$\zeta(t,x,y,z) = \frac{1}{2\pi^2}\mathrm{Re}\int_{-\infty}^{\infty} d\alpha \int_{\mathcal{C}} ds\, s\frac{\tilde{L}(s,\alpha)}{L(s,\alpha)+\tilde{L}(s,\alpha)}Q_E(s,\alpha)E_1(t-\tau(s,\alpha)), \qquad (1)$$

where L, $\tilde{L}$, and Q_E are functions of the variables s and α only, and E_1 is a causal function of time. The representation (1) has a simple physical meaning. The integration with respect to s accounts for the contribution from a particular point on the reconnection line marked by α, whereas the integration with respect to α sums up the contributions from all points on the reconnection line. Once the displacement vector (1) has been obtained, all other MHD quantities can be derived from the displacement vector.

3 Results and discussion

To model a pulse of reconnection one has to specify the dependence of the reconnection rate as a function of time, e.g.,

$$E^*(t,y) = 12\, t^2 e^{-4t}\frac{a}{\pi(a^2+y^2)}, \qquad (2)$$

with a maximal reconnection rate of $E^*_{\max} = 0.2$. As a function of y, the electric field has a maximum at the origin and then decreases with y. Hence, the constant a in (2) represents an effective length L_X of the reconnection line.

For the case of skewed fields all shocks and discontinuities launched by reconnection move not only with different de Hoffmann-Teller velocities but also they move in different directions. As a result, the BL regions which consist of accelerated and heated plasma are highly elongated with progressively increasing distance between all discontinuities.

Each discontinuity produces disturbances in the outer regions corresponding to the poles of the source term Q_E. In addition, surface waves connected with the poles of $L+\tilde{L}$ in equation (1) must be present. Although the whole structure looks complicated, it is still possible to identify the basic features of skewed field reconnection. First of all, one has to find the location of the BL region. The Alfvén discontinuities above and below the current surface propagate with different Alfvèn velocities $\mathbf{v}_A + \mathbf{v}_0$, $\tilde{\mathbf{v}}_A + \tilde{\mathbf{v}}_0$, and in the course of time t, they displace to the positions $(\mathbf{v}_A + \mathbf{v}_0)t$, $(\tilde{\mathbf{v}}_A + \tilde{\mathbf{v}}_0)t$. Also, the magnetic field between those discontinuities inside the BL region is directed along the vector $\mathbf{v}_A + \mathbf{v}_0 - (\tilde{\mathbf{v}}_A + \tilde{\mathbf{v}}_0)$. The scale of the MHD disturbances in the surrounding medium depends on the reconnected flux as well as the size and direction of the reconnected fields. The investigated patterns of MHD perturbations at different locations of a satellite are presented in dimensionless units as functions of time for skewed fields in Fig.1.

4 Conclusions

An analytical solution of 3–D time dependent reconnection in compressible plasma with moving shocks is presented. The moving slow shocks and Alfvén discontinuities excite disturbances in the surrounding media. Solutions for a space and time varying reconnection rate are obtained which include coupling of all types of MHD waves (MHD discontinuities and linear slow, fast and Alfvén waves) under the pressure balance condition. The theory can be used for detailed analisys of perturbations of magnetic field, pressure, mass density, plasma velocity at various positions of a satellite.

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